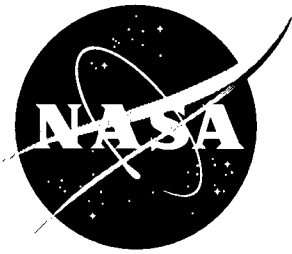


The Microgravity Research Experiments (MICREX) Data Base

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I. Interest in Low-Gravity Fluid Dynamics

Throughout the past four decades, scientists, mathematicians, and engineers have become increasingly interested in reduced-gravity fluid statics and dynamics. As a result of this interest, hundreds of experiments have been performed in a reduced-gravity environment to study the benefits and trials of low-gravity fluid response.

1. Problematic Flow Fields Related to Early Rocket/Spacecraft Design

Much of the initial interest in low-gravity fluid statics and dynamics was generated during the design of early rocket and spacecraft fluids systems. During this time, a significant amount of research was performed to study reduced-gravity liquid/vapor (free-surface) interface behavior. Control of such interfaces was expected to be problematic in many space systems including partially filled propellant tanks, space power systems (evaporators/condensers), and spacecraft life support systems (water storage, vapor ventilation).¹

Much of the initial research concerning such interfaces was related to the low-gravity behavior of propellants in partially-full fuel tanks.² Most of the early experiments related to such systems were initiated to study several aspects of propellant tank fluid management including shape and location of the interface, separation of the liquid and vapor, interface dynamics and equilibrium, and heat transfer.

A multitude of terrestrial-based reduced-gravity experiments were performed which indicated that the static and dynamic behavior of the liquid in spacecraft systems (and the associated liquid heat transfer) would be dependent on (1) a variety of reduced-gravity steady and transient acceleration disturbances (vehicle drag, vehicle motion, crew motion, etc.) and (2) gravity-independent forces.

Early mathematical and experimental analyses of the forces acting on the stored propellant, indicated, for example, that low-gravity fluid systems were dominated by intermolecular or surface tension forces (not inertial forces as in terrestrial fluid systems). It was suspected and later verified that propellants partially filling a container in a reduced-gravity environment (1) assumed a shape that minimized the liquid's surface energy and (2) had a final fluid distribution that was dependent on the wetting nature of the fluid to the container and other factors. This meant that without preventative measures, propellants could not be expected to be distributed at the desired position (e.g.,

the fuel inlet), and might instead float free within the container or become attached at some point(s) to the container wall.

Because the tanks most often stored the liquid for engine restart operations, the systems had to be designed to insure liquid (not a liquid/vapor combination) was available at the pump inlet. It was recognized that if acceleration and heat transfer perturbations combined with surface tension forces were sufficiently severe to move liquid completely away from the area of the pump inlet, the liquid would have to be recollected at the inlet by acceleration of the vehicle (via ullage rockets) along the thrust axis (before attempting to restart the engine).¹

Heat transfer conditions were also of great concern. Heat gains during long storage periods were expected to contribute to the production of excess vapor. Thus, experiments related to correct positioning and venting of the vapor were also formulated.

2. Problematic Flow Field Challenges of Today

Although the liquid/vapor problematic flows directly related to early rocket/spacecraft design were addressed, capillary-dominated and problematic/deleterious flow fields still plague and challenge scientists and engineers who must overcome or address similar flows in a variety of applications. Reduced-gravity fluid wetting, fluid flow, fluid configuration, etc., must be predicted, analyzed, and/or accounted for in such areas as (1) modern orbital propellant configuration, (2) orbital propellant transfer, (3) heat pipe technology, (4) liquid bridge formation, (5) water dispensing, (6) firefighting, (7) desired immiscible fluid separation, (8) elimination of free surfaces during contained melting, etc.

3. Beneficial Flow Fields

Although the challenges of problematic reduced-gravity fluid flow have and will continue to challenge engineers, more recent experimental efforts have focused on the expected benefits of low-gravity fluid dynamic flow fields.

Preliminary analyses of equations and boundary conditions governing fluid systems of interest, for example, have indicated that a variety of low-gravity fluid systems should experience a reduction in buoyancy-driven convection, particle sedimentation/buoyancy, and/or hydrostatic pressure. Such reductions, in turn, are expected to produce more favorable flow fields in comparison to their Earth counterparts. In addition to these advantages, containerless processing of materials should be

II. Ground-Based Reduced-Gravity Experimental Facilities

Terrestrial-based facilities that have been historically employed as low-gravity test beds include (1) aircraft, (2) drop towers, and (3) drop tubes. These facilities, most of which were first utilized during early rocket development, provided users with very short-duration low-gravity environments. All three types of facilities are still employed today and are used to model the trials and benefits of reduced-gravity fluid systems.

As discussed by Naumann⁵ and Salzman,⁶ "low-gravity" or "reduced-gravity" test beds are produced when an experiment facility is placed in a state of free fall. During the free fall, the force of gravity on the experiment is offset by its linear acceleration during the fall.⁶ When ground-based facilities are employed, this period of free fall is very short (typically <30 seconds) and most often comes to an abrupt end (e.g., deceleration of the experimental apparatus in a drop tower). When an orbiting spacecraft in the state of perpetual free fall toward the Earth is employed, "reduced-gravity" periods are very long, and experimentation is completed prior to termination of the "low-gravity" environment.

Although the terrestrial-based facilities offer only minimal reduced-gravity experimental time, there are many benefits associated with such research. For example, because it has been repeatedly demonstrated that the results and/or trends of fluid behavior obtained during terrestrial reduced-gravity experimentation are often verified/extended during later space experimentation, the terrestrial facilities provide a relatively inexpensive test bed at which (1) scientific understanding of many phenomena is advanced, (2) proof-of-concept or precursor experiments can be performed, (3) multiple experiment reconfiguration and retry can be realized, (4) space flight hardware can be evaluated (prior to extended low-gravity operation), (5) less stringent experiment safety requirements can be imposed (compared to manifested space missions), and (6) varying investigations can be performed (without major facility modification).^{7,8,9}

1. Aircraft Low-Gravity Test Beds

Once it was mathematically determined that aircraft could fly in parabolic trajectories to produce reduced-gravity conditions, F-94, T-33, F-100, and F-104 fighters were employed by the U.S. Air Force to perform the maneuvers.¹⁰ (It was noted that the F-104B could produce "relatively pure weightlessness for 40 seconds.") During these preliminary studies, the effects of the reduced-gravity environment on the crew and aircraft were observed. Short-term evaluation of crew physiological functions revealed

possible in the reduced-gravity environment. Such processing is expected to produce materials without the typical nucleation sites and contamination often attributed to the presence of container walls.³

Thus, once spacecraft could attain Earth orbit, and long-duration experimentation looked promising, more and more experiments designed to study the benefits of reduced-gravity fluid flow were formulated and proposed. When further analysis and low-gravity experimentation indicated that the thermal fields, solutal fields, particle distribution, and/or fluid configuration associated with several of these low-gravity fluid systems were expected to be desirable for many materials processing initiatives, scientists and mathematicians anticipated that great advances might be made in an entire realm of materials processing endeavors. These advances were to include not only the production of superior materials in space, but also an improved understanding of fluid processes governing a multitude of materials fluid systems.

4. Low-Gravity Research Related to Proving Flow Theory and Examining Secondary Flows

In addition to improved materials processing endeavors envisioned by scientists, mathematicians have long viewed low-gravity experimentation as an opportunity to further prove/disprove fluid flow theories and to determine the role of fluid processes in fluid systems. In the absence of (or more realistically, the reduction of) gravity-dependent fluid phenomena, flow equations are often simplified to permit examination of the effect of gravity-independent flows on the fluid system. Gravity-independent Marangoni flow, electroosmotic flow, Stefan flow, and Soret diffusion³ can be studied without interference from gravity-dependent phenomena. This in turn, is expected to lead to increased fluid flow prediction and control. Once the role of each fluid process/parameter is understood, experiments might be better designed to achieve the flow fields desired.

5. Low-Gravity Systems Exhibiting Both Problematic Flow Fields and Beneficial Flow Fields

Analysis has also indicated that several fluid systems would be affected both positively and negatively by reduced-gravity fluid response.⁴ In the low-gravity, semicontainerless float-zone melt, for example, the fluid system should be positively affected by (1) a reduction of circulatory buoyancy-driven convection (improving temperature and concentration distributions near the solidifying interface), (2) a reduction of hydrostatic pressure

(resulting in the formation of longer, more stable zones), and (3) reduced wall effects (such as contamination and nucleation at the zone wall). On the other hand, the semicontainerless melt may be negatively affected by a second type of convection that may be initiated and sustained by thermal and solutal gradients along the zone free surface. This convection, which is gravity independent, is known as Marangoni convection, and results because fluid elements on the free surface with a low surface tension tend to flow to fluid areas of higher surface tension. Often, the convection produces oscillatory temperature gradients within the reduced gravity system and thus reduces the compositional homogeneity of the processed crystal.

Such Marangoni convection also occurs in ground-based floating zone melts, but in the terrestrial laboratory, buoyancy-driven convection usually masks the underlying contribution of surface-tension-driven effects. Even though the Marangoni flow is problematic, the reduction of the gravity-dependent contributions permits a closer examination of surface-tension forces and their critical role in driving thermal and mass transport within the zone.

tendencies toward nausea, blood pooling, etc.; evaluation of the aircraft indicated that wing-flap motors and inverters were damaged by engine heat and lack of air circulation during the reduced-gravity period.¹⁰ Although it was desirable that experimental apparatuses also be carried on these flights, available cabin area was limited and most equipment had to be placed on the lap of a crew member (with no interference to aircraft canopy closure or ejection seat operation).¹⁰

In 1958, a program was defined by the Aeronautical Systems Division of the Air Force to provide a reduced-gravity environment large enough for a man to free float during the maneuvers.¹⁰ A propeller-driven C-131B aircraft that had a larger cabin area for a laboratory was proposed for these studies. These aircraft were modified for reduced-gravity flight (e.g., prevention of propeller overspeeding if oil pressure was lost during the parabola) and by the late 1950's, were employed to typically produce 12- to 15-second, unsteady low-gravity test beds (approximately 10^{-2} g).^{10,11} A short time later (1960), the jet-powered KC-135 aircraft (originally flown by the Air Force and then later by NASA), was also employed for the early studies.^{10,11,12,13}

Although the aircraft were initially used to examine the response of humans to the low-gravity environment, they were soon employed to study low-gravity fluids response. Some of the first experiments performed on the aircraft were initiated to obtain baseline low-gravity fluid configuration and control data related to propulsion systems.^{10,11} Initially, experiments were attached to the floor of the payload bay, but later, apparatuses were allowed to free float unrestrained, with observers intervening only if collisions appeared imminent.¹⁰

Later research efforts related to problematic flow fields included (1) low-gravity fluid boiling and condensation characteristics, (2) flame and combustion characteristics, (3) fuel configuration in spacecraft reaction and control rockets, and (4) low-gravity propellant manipulation via wetting on metallic screens.^{10,11}

Similar aircraft are still employed today for such reduced gravity studies. During the flights, researchers can monitor and reconfigure experiments in real time during/between the trajectories.¹⁴ One of the most popular reduced-gravity airplanes used today is the (modified) Boeing KC-135, flown from Ellington Air Field (Houston, Texas).¹⁵ A typical KC-135 parabolic flight trajectory is illustrated in figure 1 (Reference (15)). During the maneuver, the plane climbs rapidly at a 45° angle, slows at the top of the parabola, and finally descends at a 45° angle. The forces of acceleration and deceleration are twice that of

normal gravity during the ascent and descent sections of the flight, while the brief time at the top of the parabola produces less than 1 percent of the Earth's gravity.¹⁶ Typically, this up and down (roller-coaster) pattern is repeated several times during the flight. Up to 40 trajectories can be performed in the newer KC-135A during one 3-hour flight, each trajectory providing 25 to 30 seconds of reduced gravity conditions.^{7,12,15}

The KC-135 vehicle is equipped to provide electrical power, gas sources (including air and nitrogen), communications equipment (intercom), overboard fluid/gas venting, and photographic coverage.^{13,15} Investigators provide experiment hardware and sample materials and determine the in-flight experimental procedure.¹⁷ Typically, an experiment assembly is either bolted to the floor of the aircraft or allowed to float freely about the available volume of the payload area. (Bolted assemblies typically experience 10^{-2} g acceleration levels; freely floating assemblies 10^{-3} g's.)¹⁴

Today, the KC-135, KC-135A, and the Learjet Model 25 aircraft continue to be employed by NASA¹⁴ to examine a wide variety of scientific endeavors including (1) the evaluation and design of hardware to be flown on extended low-gravity missions, (2) low-gravity fluid transport and fluid interfacial studies, (3) low-gravity heat transfer studies, (4) reduced-gravity gas combustion investigations, (5) containerless processing/studies using acoustic or ultrasonic levitation, (6) low-gravity welding demonstrations, (7) low-gravity melt-crucible interactions, (8) contained directional solidification experiments, etc.^{18,19}

2. Drop Towers

The early 15-second aircraft reduced-gravity studies were complemented by even shorter-duration terrestrial drop tower experiments. One of the first drop towers available for such experimentation was at the NASA Lewis Research Center (LeRC). The facility, which had previously been employed at the Center as a fuel distillation tower, was initially used as a low-gravity test facility in the late 1950's and continues to be employed today. Detailed descriptions of the tower can be found in References (6, 7, 14, and 20).

The tower is depicted in figure 2 (Reference (20)). The top of the tower is equipped with an aerodynamic canister (complete with drag shield), into which an experimental package (weighing less than 150 kg) is placed. Once the fluids in the package are stabilized and the research team is ready, the canister is released. As the experimental package/canister free falls approximately 30 m into a 2.1-m deep sand pit below, the experiment package

floats freely within the canister.^{7,8,21} During the fall, high-speed motion picture cameras are used to record fluid response; thermocouples, pressure transducers, etc., document other relevant data. Deceleration levels at impact vary from approximately 40 to 100 g's for several milliseconds. At impact (and earlier at free-fall initiation) the fluid system experiences a step change in gravity that can produce large transient effects in the fluid system.²⁰

Reportedly, over 10,000 test drops have been conducted in the LeRC facility since it was first employed and 1,000 test drops are routinely performed each year (up to 15 drops can be performed in one day).^{7,20} Although the tower can provide only 2.2 seconds of reduced-gravity environment (at a gravity level typically less than 10^{-5} g),¹⁴ this level is lower than that attainable in modified jet aircraft flying in parabolic trajectories.²⁰

Early drop tower experiments at LeRC were performed to determine how and what factors (contact angle, surface tension, etc.) affect reduced-gravity liquid orientation. The research was then extended to study propellant configuration in partially filled tanks.

The above mentioned LeRC drop tower and other similarly designed drop towers (such as the tower at Marshall Space Flight Center (MSFC)), were eventually employed to perform experiments designed to examine the benefits of reduced-gravity fluid response. For example, in the early 1970's the 100-m (4.2-s) MSFC tower (fig. 3)¹⁴ was first used to perform ground-based experimentation related to low-gravity materials processing.^{17,20,22,23} (The tower had originally been used to investigate Saturn V/S-IVB stage orbital propellant behavior.)^{24,25} One of the first of these materials experiments was initiated to examine the possibility of containerless processing. During the study, a variety of fluids (mercury, glycerin, and glycerol) were employed to study reduced-gravity (containerless) sphere formation, deployment, and oscillation.^{17,22} These studies were complimented by other drop tower experiments designed to demonstrate the feasibility of employing magnetic fields for the positioning and processing of containerless solid-and-liquid materials (i.e., metallic spheres).¹⁷ Other early MSFC drop tower experiments included the rapid cooling and solidification of low-temperature melting immiscible metals such as gallium-bismuth.^{5,26} Although the MSFC drop tower is currently not being employed for such studies, other available drop facilities continue to provide reduced-gravity test beds for a variety of experiments. For example, more recently, the LeRC towers (the aforementioned 2.2-s facility and an additional sophisticated 5.18-s (10^{-6} g) vacuum facility)) have been employed to examine many fluid systems including (1) solid fuel

flame spread, (2) diffusion flame combustion, (3) droplet combustion, (4) surface tension-driven convection, (5) multiphase/multifluid forced flow through a conduit, etc.¹⁴

3. Drop Tubes

A drop tube differs from a drop tower in that single, containerless liquid/molten samples (not scale-model experimental packages) are allowed to free fall the length of the tube (fig. 4).³⁰ Using such a facility, large amounts of undercooling in metals and alloys can be achieved by allowing the sample to free fall without contacting any external surfaces. A furnace (contained within a bell jar) at the top of the tube melts the material of interest and then the drop is released to fall the length of the vertical tube.²⁹ (Both the bell jar and tube are evacuated to the desired pressure.) The tube can be backfilled to provide for increased cooling of materials. Samples are decelerated and caught by catchers. Using this method, experiment duplication is relatively easy and cost effective (when compared to sounding rocket or manned space flight experimentation).

The original drop tube at MSFC (built in 1976)³⁰ was 30-m long (10-cm diameter), and provided 2.6 s of reduced-gravity (or free-fall) time.²⁹ The facility was built after preliminary analyses of Skylab containerless processing experiments indicated that additional reduced-gravity research of uncontained, molten liquid drops was necessary.²⁷ The first materials examined in the drop facility included niobium and niobium-germanium alloys.

In 1980, a longer tube was built at the Center.³⁰ This longer tube (105-m (25-cm diameter)) is still employed today and allows 4.6 s of free-fall time.³¹ To date, over 5,000 experiment samples have been dropped in the facility and evaluated.³⁰

The tube is long enough to solidify a wide range of materials from the melt. Recent research efforts in the tube include the containerless solidification of a number of high and low melting temperature metals and alloys. For example, containerless niobium-platinum samples, which melt at high temperatures and are highly reactive with crucible materials, have recently been undercooled and solidified in the low-gravity facility, illustrating complete solute trapping.²⁸

Additional information on the drop tube can be found in Reference (32).

III. Suborbital Sounding Rockets

Longer duration reduced-gravity experimentation was performed on (1) suborbital sounding rockets (beginning in the early 1960's) and (2) pods ejected at a suborbital altitude from the Atlas intercontinental ballistic missile (in the mid 1960's). These early experiments were primarily related to the study of liquid/vapor (free surface) interfaces. Beginning in the 1970's, suborbital rockets were employed to produce 4 to 6 minutes of reduced-gravity for experiments designed to examine the benefits and trials of reduced-gravity materials processing. Since that time, experimental endeavors in such sounding rockets have continued and the rockets have become a popular source of extended-duration, low-gravity research (typically 6 to 7 minutes). Currently, a wide variety of scientific investigations are carried on the vehicles including crystal production, cell fusion, physical chemistry, fluid dynamics, etc.

1. Early Experimentation Related to the Study of Problematic Flows Encountered in Rocket/Spacecraft Design

A. Experiments on the Aerobee Sounding Rocket

Beginning in the 1960's, experiments designed to examine low-gravity liquid behavior and problematic flow fields associated with partially filled propellant tanks were carried in the front end of the Aerobee 150A (suborbital) sounding rocket.^{2,33,34,35} Typically, the experimental package included (1) a 9-in spherical scale-model propellant tank partially filled with liquid hydrogen (and configured with heaters and thermocouples), (2) telemetry equipment to transfer thermocouple and other data, and (3) a camera to document liquid/vapor configuration. The major objectives of these missions included (1) subjecting the partially filled dewars to controlled, radiation-heated environments; (2) determining the resulting fluid configuration under reduced gravity conditions; (3) determining the heat transfer between the container wall and employed fluid; and (4) examining the rate of pressure rise in the closed hydrogen dewar.

The major components of the Aerobee rocket (with details of the payload section for flight No. 2) are depicted in figure 5 (Reference (34)). Since the Aerobee was a spin-stabilized vehicle, the experiment was placed on a spin table within the payload section. Although it is not specifically stated in the available references, it appears that the spin table rotated counter-clockwise to the rocket, thus insuring that the dewar and other equipment were maintained at an (effective) zero spin rate during rocket boost.^{2,33,34} In addition, the rocket contained helium thrust nozzles that were used to compensate for the an-

ticipated air drag encountered immediately after sustainer burnout and hence to extend the reduced-gravity period. Although not indicated in figure 5, accelerometers were housed in the vehicle to document reduced gravity levels.³³

The two-stage, solid-propellant Aerobee 150a rockets, which typically carried experimental payloads weighing approximately 300 lb., were launched from Wallops Island, Virginia. Flight sequences for four of the flights are given in References (2, 33, 34, and 35). (It appears that at least 9 such Aerobee flights were realized during the program before its termination.) The major events during flight No. 9 (as detailed in Reference (2)) were described as follows: 53 s after launch, second-stage (sustainer) burnout occurred at an altitude of 110,000 ft. Approximately 30 s later, rocket despin occurred and the trajectory experienced a reduced-gravity environment (10^{-4} g) for approximately 4.5 min. During this time, the trajectory attained a maximum height of 102 mi as it continued its ballistic, free-fall trajectory. Throughout the flight, liquid hydrogen configuration and heat transfer characteristics were recorded.

Although flight No. 9 did not contain a movie camera for the documentation of solid/liquid/vapor configurations, some of the flights were equipped with such equipment. These cameras were housed in a recovery capsule that separated from the remainder of the payload (after approximately 350 s of flight) and parachuted into the Atlantic Ocean. Air and surface craft were employed to search for the capsules.³³ <Note: References (2, 33, 34, and 35) did not detail the recovery procedures (if any) for the rocket/experimental-payload. Reference (36) indicated that the experiment parachuted into the water and was recovered by the U.S. marines.>

B. Experimental Pods attached to the Atlas Intercontinental Ballistic Missile

In the mid 1960's, even longer duration low-gravity experimentation was achieved in experiment pods initially attached to the Atlas intercontinental ballistic missile. The pods, which were ejected from the Atlas at a higher (yet suborbital) altitude than that of the Aerobee sounding rocket, experienced approximately 20 to 30 minutes of reduced-gravity experimental time. Available references did not indicate how many such pod ejection flights were performed before the program was terminated.

Research objectives of experiments contained within a pod were nearly identical to those of the Aerobee. However, while most of the Aerobee research had indicated that the low-gravity time available on the rocket was sufficient to establish steady-state

or limiting conditions, the research also indicated that if a low heat flux (25 Btu per hour per square foot) was imposed on the liquid hydrogen dewars, more time was required to reach quasi-equilibrium or limiting conditions (so that time extrapolated predictions could be made).³⁷

The Atlas passenger pod experimental hardware was similar to that of the Aerobee hardware, but the pod carried two differing diameter, partially filled subscale propellant tanks. Thus, tank scaling effects related to the study of heat transfer characteristics could be determined.³⁶

The experiments were configured in the 8.5-ft. long, 30-in diameter pod with the necessary associated hardware. In addition to the telemetry system and other equipment, the pod contained a mass stabilization system. The system was included to attenuate any acceleration perturbation to the pod that might be imparted by the vehicle or ejection mechanism.³⁷ (For more information see Reference (37)). Figures 6 and 7 (Reference (37)) illustrate the flight experiment mounted in the passenger pod (fig. 6) and the pod mounted on the Atlas missile (fig. 7).

The Atlas vehicle with its "piggy-back" pod was launched from the Atlantic Missile Range in Florida. A pod flight history was detailed in Reference (37). Fifteen seconds after pod ejection, the mass stabilization system was enabled. During this particular flight, a malfunction of the circuit controlling the stabilization system occurred and as a result, the experiment experienced an acceleration field on the order of 10^{-3} g during the reduced gravity period (8 to 29 min after lift-off). During the flight, measurements of the hydrogen dewar wall temperatures, the liquid hydrogen thermal profiles (and relative positions of the gas ullage), dewar pressures, pod acceleration level, etc., were telemetered to the ground and recorded on magnetic tape (no cameras were available in the pods). No attempt was made to recover the pod itself.

2. Recent Experimentation Related to the Study of Beneficial Flow Fields

Since the early 1970's, scientists and engineers have become increasingly interested in employing the low-gravity environment to achieve beneficial flow fields. This interest escalated in the mid 1970's after extended-duration spacecraft experimentation on Skylab and the Apollo-Soyuz Test Project (ASTP) demonstrated (1) promising materials processing results and (2) intriguing fluid dynamic observations (see pp. 28-31).

A. Initial U.S. Materials Processing Experimentation on the Aerobee and Black-Brant Sounding Rockets

MSFC materials processing experiments were configured on sounding rockets soon after the Apollo 14 mission.

In December 1969, Apollo 14 carried a composite casting (materials processing) experiment designed to produce materials with improved or unique mechanical, electrical, and/or optical properties.³⁸ During the mission, only 11 of the 14 experiment capsules were processed. In May 1971, a co-investigator of the Apollo experiment (H. Wuenschel of MSFC), visited Goddard Space Flight Center (GSFC) to ask if an unused composite casting experimental capsule (and the associated processing facility) could be placed on a GSFC sounding rocket.³⁸ (Rockets such as the Aerobee 170A and the Black Brant VC were being tested and evaluated at the time by the engineers at the GSFC Sounding Rocket Division.) It was determined that the experiment hardware could be placed on an Aerobee 170A rocket if the lead ballast that often makes up part of the vehicle payload was removed.¹⁷

The employed Aerobee 170A, which was composed of a three-fin Aerobee 150A liquid propellant sustainer and a solid propellant Nike booster, was launched specifically by GSFC to evaluate the dispersion characteristics of the vehicle. The secondary (piggyback) materials processing experiment, which flew as planned in a small area of the payload section, was implemented by MSFC engineers to not only process the Apollo sample, but to determine if such rockets were suitable for reduced-gravity research.

The rocket was launched in October 1971 from the U. S. Navy Ordnance and Missile Test Facility (USNOMTF), in White Sands, New Mexico. The rocket reached an altitude of approximately 150 km and experienced a reduced-gravity time of 220 s. The vehicle was equipped with accelerometers, and despun with a yo-yo despin system. (The despin was accomplished by deploying weights on the ends of cables that were attached to the vehicle.)¹⁷

The piggy-back experiment was designed to investigate the stability of gas bubbles in a plain and fiber-reinforced metal melted and solidified in a reduced-gravity environment.¹⁷ The employed single sample had two distinct halves. The a-half consisted of interconnected gas cells in a fiber-reinforced metal matrix; the b-half consisted of discrete gas bubbles in a plain metal matrix. During the flight, the sample was to be heated such that a phase change from solid to liquid occurred.³⁸

Post-flight examination of the sample indicated that the a-half of the sample had not been heated sufficiently to provide meaningful results and that the b-half of the sample experienced only partial melting. It was reported that "In the areas which appeared to have melted, three conditions were noted: some bubbles had disappeared, some bubbles had coalesced, and some bubbles remained in place."¹⁷ References 17 and 38 further detailed the experimental results.

<Note: It appears that an unused Apollo 14 experimental capsule was not employed in the Aerobee experiment as originally planned. Reportedly, the sample processed on the Aerobee 170A was "designed and fabricated for the Apollo 15 'Composite Casting Demonstration'" experiment.¹⁷ (The sample most likely became available when the composite casting experiment was removed from the Apollo 15 manifest.)>

A similar sample was flown on a Black Brant VC sounding rocket in 1972. Again the experiment flew piggy-back on a vehicle that was launched to primarily test and verify the rocket performance. Unfortunately, during flight, the heat shield was not separated from the payload and the experiment was lost.¹⁷

After the two rocket flights were evaluated, it was concluded³⁸ that the sounding rockets, equipped with altitude control systems and sufficient payload despin systems, provided a good environment for materials processing experiments.

B. The U.S. Space Processing Application Research (SPAR) Program

B1. The SPAR Program Initiation and Experimental Emphasis

Although flying experiments one-at-a-time (piggy-back) on sounding rocket test flights was relatively inexpensive compared to the cost of purchasing rockets to specifically carry reduced-gravity experiments, there were several advantages to implementing a sounding rocket program dedicated to low-gravity fluids and materials processing research. Among these advantages were (1) an increased payload area available for experimentation and (2) rocket altitude control and despin systems specifically designed to produce the desired reduced-gravity research environment.

The first sounding rocket program dedicated to exploring and developing techniques for processing a variety of materials in a reduced-gravity environment was the SPAR program. The SPAR project was a NASA activity, directed by the Office of Space and Terrestrial Applications (OSTA). (OSTA was later renamed the Office of Space Science and Applications (OSSA).) The program was initiated to permit development and testing of reduced-gravity

experimental concepts at a time when manned spaceflight opportunities were not available (between the ASTP mission and the U.S. space shuttle missions).⁵ Reportedly, SPAR experimentation was performed to help define future shuttle fluids and materials processing investigations.

The SPAR rockets, which were first launched in 1975, were capable of providing 4 to 6 minutes of reduced-gravity experimental time. During its brief history (10 flights between 1975 and 1983), SPAR carried approximately 70 experiments (typically 5 to 8 experiments per flight). Approximately 50 of the SPAR experiments were related to fluids or materials processing research and included (1) the directional solidification of magnetic composites, (2) containerless processing technology (liquid drop stability and manipulation), (3) alloy solidification, (4) liquid mixing due to spacecraft motion, (5) dispersion of immiscible materials, (6) multiphase particle interaction, (7) closed-cell metal foam production, and (8) dispersion strengthening composites.³⁹

B2. The SPAR Vehicle, Launch and Performance

The program typically employed single-stage, solid-propellant Black Brant VC rockets (SPAR flights 1 to 5, and flight 10). The rockets were powerful enough to place a science payload of approximately 400 lb in a reduced-gravity environment (10^{-4} g) for 5 minutes.^{39,40} The SPAR 2 (designated as SPAR II) total rocket configuration is presented in figure 8 (Reference (41)).

A Black Brant VC rocket with a Nike boost was employed to accommodate heavier payloads or to achieve reduced-gravity periods of longer duration (SPAR flights 6 to 9).

The payload section of the SPAR included (1) interchangeable experiment modules, (2) a measurement module (housing tri-axial accelerometers), (3) an experiment support module, (4) a telemetry system, (5) a despin system, (6) a rate and control system,⁹ (7) a payload destruct system, and (8) a payload recovery system.

The vehicles were launched from White Sands Missile Range, New Mexico. The flight profile of SPAR 10 is detailed in figure 9 (Reference (39)). During the SPAR 10 mission, the employed spin-stabilized rocket attained an altitude of approximately 60 km before the rocket propellant was exhausted. At this altitude, the rocket was despun and the payload separated from the rocket.³⁹ After separation, a rate control system insured that residual rotational rates were attenuated. During the following unpowered coast phase, the payload experienced approximately 5 min of reduced gravity (typically 10^{-4} g; apogee approximately

180 km). After the conclusion of the low-gravity coast phase, a parachute system was deployed, and the payload was retrieved on land by helicopter (82 km down range).³⁹

C. The Japanese TT-500A Sounding Rocket Program

C1. The TT-500A Program Initiation and Experimental Emphasis

A sounding rocket program dedicated to studying reduced-gravity materials processing was initiated in Japan in 1980. The effort, known as the TT-500A sounding rocket program, was developed by the National Space Development Agency of Japan (NASDA) and continued for 3 years. During this time, six rockets were launched, each typically carrying 2 to 4 electric furnaces within its payload section for the processing of metallic alloys or semiconductors (flights No. 1 to 5).⁴² Flight No. 5 also housed a halogen lamp system experiment; flight No. 6 evaluated (1) an electric furnace (composite fabrication), (2) an image furnace (composite fabrication) and (3) an electric furnace with an acoustic mixer (immiscible alloy production). The program was terminated after six launches due to budgetary limitations.⁴³

The TT-500A program had two major goals, both of which were related to Japan's (then future) experiments on the U.S. space shuttle.⁴⁴ (These future experiments were known as the First Materials Processing Test (FMPT) and were later flown on the shuttle during STS Spacelab-J (September 1992)). The first goal was to provide a reduced-gravity test bed for some of the FMPT materials processing experimental concepts/hardware. The second goal was to ensure functional coordination between Japanese ground-based facilities that would later be used during the U.S. shuttle flight (the Tanegashima Space Center and the Ogasawara Down-Range Station).

C2. The TT-500A Vehicle, Launch and Performance

Prior to the initiation of the TT-500A materials processing program in 1980, there were seven test flights of the TT-500 rocket to verify its performance. The numbering sequence of the materials processing flights were therefore TT-500A 8 (flight No. 1), TT-500A 9 (flight No. 2), etc.⁴⁵ TT stands for "Tracking Test," "500" represents the rocket diameter (500 mm) and the "A" indicated that the rocket was improved from the original TT-500 rocket (to include installation of experimental devices, attitude control systems, and a recovery system).^{42,43}

The vehicle was designed to carry a materials processing system with a maximum mass of 135 kg (330 kg total payload weight).^{42,46} The small, two-stage, solid-propellant rocket weighed 2.35 tons and stood 10.5-m high (including the 2.7-m payload section).^{44,47} The major components of the vehicle are depicted in figure 10 (Reference (44)).

The rockets were launched from the Takesaki launch site on Tanegashima Island. A nominal rocket trajectory is depicted in figure 11 (Reference (44)). Typically, second-stage burn-out occurred at 50 s after launch and payload separation followed shortly thereafter. The payload section was then despun by a yo-yo despinner (reducing the payload section spin rate to almost zero) and then a gas jet system insured that roll, pitch and yaw spin rates were less than 0.2 deg/s.^{42,46,47} Shortly thereafter, the experiment was initiated and experienced reduced gravity* for approximately 6 to 7 min.^{43,44,48} During this time, the payload section attained a maximum height of 320 km and continued its trajectory path to approximately 100 km (experiment termination). Parachute deployment was initiated at approximately 6 km, followed by splash down recovery (approximately 500 km offshore from Tanegashima island).^{43,44} Although the payload section was equipped with a float to permit it to stay above water, the section could not be retrieved prior to sinking after flights No. 2 and 3 (the floating system malfunctioned after flight No. 2 and the main parachute was not activated during flight No. 3).^{42,43,47}

* (Except for flight No. 1, which experienced a gravity level of 10^{-2} g due to a despin difficulty, the rest of the flights attained a gravity level of 10^{-4} g.)⁴⁷

D. The German TEXUS Sounding Rocket Program

D1. The TEXUS Program Initiation and Experimental Emphasis

In 1976, the West German government, in cooperation with Sweden, initiated a sounding rocket program dedicated to studying reduced-gravity materials processing. The effort, known as the TEXUS program (Technologische EXperimente Unter Schwerelosigkeit, or in English, Technological Experiments under Microgravity Conditions) is still operational.⁴⁹

At the initiation of the program, the West German Minister for Research and Technology charged the then named Deutsche Forschungs und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) (German Research and Development Institute for Aviation and Space Travel) with managing the program.⁵⁰ <Note: the DFVLR is now called the Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR).> The initial objective of the TEXUS program was to prepare for future ESA Spacelab utilization by flight proving experiments/hardware in advance. (The European Space Agency (ESA) had agreed to develop and build Spacelab for the U.S. shuttle program.) However, after only a few TEXUS flights, it became clear that valuable knowledge was gained during rocket experimentation that went beyond preparing for long-duration missions such as Spacelab. For example, like the U.S. SPAR experiments, TEXUS rocket experimentation (1) not only significantly illustrated the effects of the reduced-gravity environment on materials systems, but (2) also proved to be relatively inexpensive and less restrictive (when compared to spacecraft experimentation).

Thus, TEXUS soon became an independent experiment carrier for investigators wishing to carry out reduced-gravity research activities.⁵¹ Although the program was originally earmarked for experiments by domestic users, flight opportunities are currently available to scientists from other countries, especially countries which are members of ESA. Typically, it takes at least 1 year to (1) design and build the flight hardware, (2) install the hardware in the rocket module, (3) perform tests to guarantee technical functional capacities, (4) transport the rocket to the launch pad, and (5) complete final assembly of the experiment modules in the vehicle.⁵¹

D2. The TEXUS Vehicle, Launch and Performance

The TEXUS program employs a two-stage Skylark 7 high-altitude rocket (apogee approximately 250 km).⁵¹ The rockets, which can carry a payload of 350 kg, are launched from Esrange sounding rocket range in Kiruna, Northern Sweden.

The payload section of the vehicle (fig. 12)⁵² typically includes five or six 400-mm diameter interchangeable experiment modules called TEM's (or TEXUS Experiment Modules). The TEM's house a variety of experimental equipment (e.g., furnaces, etc.) which have been re-used (with some refurbishment/improvement) throughout the TEXUS program. (Sweden, which provides the launch site facilities for the rocket, also developed an experimental module to specifically house Swedish experiments on TEXUS.) Each module has its own power supply, data recording unit, and experiment controls.

The remainder of the payload section includes an instrumentation module (with accelerometers and telemetry), a yo-yo despin system, a rate and control system, and a parachute recovery system.^{9,51}

After launch, and first and second-stage burnout, the yo-yo despin system is enabled (weights suspended from cables) to reduce the rocket stabilizing rotation. Shortly thereafter, the payload section is separated from the rocket and the reduced-gravity phase (10^{-4} g) is attained and continues for approximately 6 min. <Note: Reference (53) indicated that the payload is first separated from the booster and then despun.> During this reduced-gravity phase, the payload section follows a parabolic trajectory attaining a maximum height of approximately 250 km.⁵³ The parachute recovery system lands the payload approximately 50 km from the launch pad. The payload section is retrieved by helicopter (with the help of a radio direction transmitter) typically within 1 hour of payload impact.⁵¹

At the beginning of the program, approximately one to two rockets were launched per year. Recently, four rockets have been flown per year (two in the spring and two in the fall). Of the 20 TEXUS launches detailed in this memorandum (see table 1), rocket or rocket-despin failure occurred during three of the missions (TEXUS 3a, TEXUS 15, and TEXUS 16) and a higher than desired low-gravity environment was experienced during one of the missions (TEXUS 14a).

Although over 30 TEXUS missions have been flown to date, only the experiments performed during the first 20 TEXUS missions are included in this document. (The later missions were beyond the cutoff date for inclusion in this document.)

Table 1
TEXUS flights detailed in this technical memorandum

Flight No.	TEXUS Mission	Date
1	TEXUS 1	December 1977
2	TEXUS 2	November 1978
3	TEXUS 3a	April 1980 (Rocket Despin Failure)
4	TEXUS 3b	April 1981
5	TEXUS 4	May 1981
6	TEXUS 5	May 1982
7	TEXUS 6	May 1982
8	TEXUS 7	May 1983
9	TEXUS 8	May 1983
10	TEXUS 9	May 1984
11	TEXUS 10	May 1984
12	TEXUS 11	April 1985
13	TEXUS 12	April 1985
14	TEXUS 13	April 1986
15	TEXUS 14a	May 1986 (Wobbling Motion, Low-G not Attained)
16	TEXUS 14b	May 1987
17	TEXUS 15	May 1987 (Rocket Failure)
18	TEXUS 16	November 1987 (Rocket System Malfunction)
19	TEXUS 17	May 1988
20	TEXUS 18	May 1988

E. The Swedish MASER Sounding Rocket Program

E1. The MASER Program Initiation and Initial Experimental Emphasis

In response to an increasing demand for fluids and materials processing reduced-gravity flight opportunities, a sounding rocket program was initiated in Sweden in 1987 (Reference (54)). The effort, known as the Materials Science Experiment Rocket (MASER), is still operational today and is managed by the Swedish Space Corporation (SSC). The MASER payloads attain a reduced-gravity level (approximately 10^{-4} g) for 6 to 7 minutes.

Although at least four MASER flights have been flown to date, only the experiments flown on the first two flights have been included in this document. MASER 1 was launched on March 19, 1987, and MASER 2 was launched on February 29, 1988. (The later flights were beyond the mission cutoff date for this publication.) MASER 1 and 2 carried a variety of experimental modules including (1) a fluid science module to study thermocapillary drop motion and three-dimensional Marangoni convection, (2) a mirror furnace module to investigate meniscus stability and coalescence processes in immiscible alloys, (3) a crystal growth furnace module to study semi-confined Bridgman growth of Ga doped Ge, and (4) a gradient furnace module to examine the processing of metallic alloys.

E2. The MASER Vehicle, Launch and Performance

The vehicle was designed to carry a payload with a maximum mass of 390 kg. Four to six 17-in experiment modules and other various subsystems can be configured within the modular payload area. The MASER 1 payload configuration is depicted in figure 13 (Reference (55)). In addition to the experiment modules, the payload section includes (1) a constant lateral attitude S19 guidance control system (which maintains the vehicle in the launch direction during the 18 s following lift-off), (2) a yo-yo despin system (which reduces the stabilizing spin after the launch phase), (3) a service module (which contains a variety of equipment including the telemetry system, radar transponder, batteries, power regulators, tri-axial accelerometer unit, etc.), (4) a rate control system (RCS) (to reduce angular rates in the payload during the reduced-gravity phase), and (5) a recovery module (a parachute/heat-shield/beacon-transmitter system enabling a ground impact with recovery by helicopter typically less than 2 hours after launch).⁵⁴

The rockets are launched from the Esrange sounding rocket range in Northern Sweden. The vehicle, designated Black Brant IX B, has two stages. The first stage is a three-fin Terrier booster, the second, is a three- or four-fin Black Brant VB sustainer (figure 14; Reference (54)). (MASER 1 employed a three-fin sustainer, MASER 2 employed a four-fin sustainer.)

The major events in the MASER 1 and MASER 2 flight sequences were reported in References (54 and 56). It appears that the major difference in the two flights was that payload despin occurred after separation (from the second stage) during MASER 1, while despin occurred prior to payload separation (from the second stage) during MASER 2. The MASER 2 flight sequence was reported as follows: After launch and first- and second-stage burnout, rocket despin occurred (launch plus 55 s). Five seconds later, the second stage separated from the payload section and the rate and control system was enabled. Shortly thereafter (launch plus 73 s), the reduced-gravity phase (10^{-4} g) was achieved and continued until launch plus 512 s (apogee 316 km). Approximately 110 s after the end of the reduced-gravity phase, the recovery sequence was initiated (heat shield plus initial chute deployment). Thirty-five seconds later (665 s after launch) payload impact was recorded.

F. The U.S. Consort Program

F1. The Consort Program Initiation and Experimental Emphasis

A sounding rocket program designed to support the goals of the NASA Office of Commercial Programs was initiated in 1988. The effort, which was managed by the Consortium for Materials Development in Space (headquartered at the University of Alabama in Huntsville), was called Consort. The 5-year program had two major objectives: (1) to perform materials and biotechnology investigations having commercial value and (2) to stimulate the commercial rocket industry in the U.S.⁵⁷

F2. The Consort Vehicle, Launch and Performance

The payload section of the Consort had three cylindrical compartments assembled end-to-end. An individual compartment could either be vented or sealed (to maintain atmospheric pressure) during the flight.⁵⁷ Some compartments had access doors to allow installation of equipment/samples late in the launch sequence. Although the payload section was similar to the size and length of the SPAR payload sections, the Consort vehicle could either (1) carry a heavier payload than the earlier SPAR vehicle or (2) provide a longer reduced-gravity phase than SPAR.⁵⁷

Consort employed a two-stage, Starfire I rocket. The spin stabilized vehicle, which was configured with a Thiokol TX 664 booster motor and a Bristol Aerospace Black Brant VC sustainer motor, was launched from White Sands Missile Range, New Mexico.⁵⁷ The vehicle was equipped with systems to provide guidance, telemetry, acceleration measurement, rotation rate control, and parachute recovery.

During a typical Consort flight, first- and second-stage burnout were followed by vehicle despin and then payload separation.⁵⁸ During the subsequent unpowered flight of the trajectory, approximately 6 to 8 min of reduced gravity (approximately 10^{-5} g) was realized. During this time, the trajectory achieved an apogee of approximately 300 km. A short time after the reduced-gravity phase, the payload section parachuted to the ground (approximately 100 km downrange).⁵⁷

The first Consort mission was launched on March 29, 1989. This historic mission carried the first low-gravity materials processing payload ever launched in the U.S. on a commercially licensed rocket.⁵⁹ The vehicle carried a variety of experimental investigations including: powdered metal sintering, electrodeposition and codeposition, polymer demixing, polymer foam production, etc. During the entire Consort program, a total of six rockets were launched.⁶⁰

G. The U.S. Joust Program

Another series of suborbital missions called the Joust Program (initiated by the NASA Office of Commercial Programs and managed by the Consortium for Materials Development in Space) was also planned.⁵⁷ For comparable payload masses, the Joust vehicle (which employed a Prospector rocket) was to produce almost twice as much reduced-gravity time (13 to 15 min) as the Consort vehicle. For a similar payload mass (250 kg), the vehicle was to attain a maximum altitude of 815 km (requiring an ablative heat shield for re-entry from this altitude). Although Joust 1 was launched in June 1991 from the Eastern Space and Missiles Center, (Patrick Air Force Base, Florida), the vehicle experienced a rocket failure in the aft skirt.⁶⁰ The Joust program was not further pursued.

H. Other Current Carriers

Recently (post 1989), additional carriers have been employed to place experiments in suborbital flight. These carriers include:

- (1) The German MAXUS Sounding Rocket Program (1991-present)
- (2) The Japanese TR-1A Sounding Rocket Program (1991-present)
- (3) The Canadian Microgravity Rocket (CSAR) (1992-present)

Detailed descriptions of these carriers are not presented in this document because this hardcopy version of the data does not contain summaries of these more recent experiments.

IV. Early Spacecraft Reduced-Gravity Experimental Facilities **(1962-1975)**

The manned spacecraft program provided the first opportunities for extended duration low-gravity fluids and materials processing experimentation (e.g., >20 min). The Skylab space station, which was manned by three different crews for 4, 8, and 12 weeks, respectively, provided the longest manned experimental opportunities (days, weeks). Other manned vehicles (Apollo-Soyuz Test Project and the space shuttle) provided hours or even several days for some experiments.

1. The U.S. Mercury Program

The first (manned-spacecraft) experimental payload designed to examine reduced-gravity fluid response was carried into space during the Mercury program. The experiment, which was an extension of research initiated in the ground-based LeRC drop tower, was designed to examine fluid flow in a closed container.

While drop tower experiments had illustrated that correct placement of specially-designed baffles within a container could result in the predictable positioning of the liquid vapor interface,^{21,61} the terrestrial experiments could not sufficiently illustrate if the surface-tension baffling would (1) maintain control of the liquid vapor interface during acceleration disturbances or (2) regain control of the interface after the application of large disturbing forces. Thus, in 1962, an experiment was carried on the Mercury-Aurora 7 spacecraft that was designed to (1) study the long-term, steady-state configuration of the liquid-vapor interface; (2) determine the ability of the baffle configuration to maintain control of the liquid vapor interface during spacecraft maneuvers; and (3) determine at what acceleration level (during re-entry) control of the interface was lost.⁶² A 3.3-in diameter spherical glass tank, partially filled with distilled water and configured with an appropriate baffle, was employed for the experiment. The hardware was placed in the MA-7 capsule, at a position just to the right of the astronaut's head (when he was in a sitting position). During the mission, the tank was filmed by the pilot observer camera located in the instrument panel. The results of this experiment are discussed in detail in this document on p. 12-3.

2. The U.S. Apollo Program

During early manned space flights, such as the Mercury and Gemini programs, the main objectives of the missions were to demonstrate the feasibility of space flight and man's ability to live and

work safely in space. During the subsequent manned Apollo program, man not only reached and landed on the Moon, but demonstrated that his involvement in the performance of experiments, observation of phenomena, and operation of the spacecraft was invaluable.⁶³ Throughout these early flights, there was little emphasis on examining beneficial or problematic fluid phenomena in detail, and experiments designed to study fluids or materials processing initiatives were rarely included in the flight manifest. However, during the Apollo 14, 16, and 17 missions, several small "suitcase" experiments were added to the flight.

The investigations, which were performed during the trans-Earth coast, included (1) a liquid transfer experiment that demonstrated the draining and filling of model storage tanks (Apollo 14), (2) a simple heat flow experiment that illustrated the low-g reduction of buoyancy-driven convection and the presence of Marangoni convection (Apollo 14 and 17), (3) a low-temperature furnace capable of casting model composite systems (four experiments on Apollo 14), and (4) two primitive electrophoresis demonstrations (Apollo 14 and 16). Reportedly, "The power and weight available for such experiments greatly limited their capability and the scientific details that could be obtained from them. All of the experiments operated successfully but revealed the presence of more subtle nongravitational flows that needed further understanding before the microgravity environment could be used to advantage."³ (The experiments are detailed in this document on pages 12-7 (draining and filling of tanks), 12-13 to 12-21 (convection experiments), 5-3 to 5-13 and 17-3 (casting experiments), and 1-3 to 1-9 (electrophoresis).)

3. The U.S. Skylab Program

Unlike the Apollo program, Skylab was the first U.S. manned program "...with the specific purpose of developing the utility of space flight in order to expand and enhance man's well-being on Earth."⁶⁴ Experiments were performed in a number of different scientific disciplines including geophysics, stellar astronomy, biomedicine, "zero-gravity technological studies," etc. One of the specific goals of Skylab was "to develop methods for processing and manufacturing of materials utilizing the absence of gravity."⁶⁴

Reportedly, "The first materials processing experiments approved for Skylab were the welding and brazing demonstrations originally motivated by the desire to fabricate and repair space structures in space. These experiments had been under development since 1964 and were accepted for flight in 1966. As interest in processing experiments in a weightless environment grew,

facilities were expanded to accommodate five additional experiments, which were accepted in 1969. The Multipurpose Electric Furnace and 10 additional experiments were proposed in 1971 and accepted for flight in 1972."⁵

The Skylab mission was initiated on May 14, 1973, when the unmanned Saturn workshop was launched into Earth orbit (designated the SL-1 mission). During the following 272 days, nine men in three different three-man crews visited and manned the workshop. (The first crew manned the workshop for 28 days (SL-2 mission), the second crew, for 59 days (SL-3 mission), and the third crew, for 84 days (SL-4 mission).) Throughout this time, the astronauts performed scheduled and unscheduled operations with less difficulty than had been anticipated.⁶⁵

The manned presence at the laboratory was critical when several unplanned events threatened the station and/or the scientific return. For example, when a meteoroid shield, which was designed to protect the station from space particles and provide a degree of thermal shielding from the Sun deployed prematurely 63 s into the unmanned launch of the station facility and was ripped away from the Saturn IVB stage,⁶⁶ astronauts on the first manned flight were able to deploy a thermal shield that brought temperatures back to normal within a few days. The same crew was also able to deploy a solar array panel that jammed when the meteoroid shield detached from the Saturn stage during lift-off. All three of the crews performed several unscheduled maintenance tasks.

During the three manned periods in Skylab, approximately 20 experiments were performed in a facility dedicated specifically to materials processing. During the first manned mission (SL-2), a metals melting experiment, exothermic brazing, and sphere forming experiment were performed in the facility. During the second and third manned missions (SL-2 and SL-3), a multipurpose electric furnace housed within the facility was used to perform solidification, crystal growth, and other experiments. Flammability experiments were also performed in the facility during the third manned mission.^{3,65}

Fluids and materials processing experiments performed aboard Skylab benefited from the extended-duration experimental time and the astronaut presence. The long-duration mission meant, for example, that processing times could be significantly longer than those available during sounding rocket flights or the short duration Mercury and Apollo flights. In addition, impromptu science demonstrations (employing onboard equipment and astronaut ingenuity) could be performed by the crew. When a member of the the Skylab crew on the second manned mission (Science Pilot Owen Garriott) radioed to Earth that the men wished to perform science demonstrations that would (1) provide additional science data

from space and (2) "serve as time-gap fillers and to provide a change of pace for the crew...", 12 science demonstrations were proposed (within a few days) at NASA MSFC. Two of the proposed experiments were considered most compatible with Skylab III and performed on that mission (Diffusion in Liquids and Ice Melting)*.⁶⁷ Between Skylab III and IV (less than 52 days), 17 additional science demonstrations were defined in anticipation of excess crew time on Skylab IV. Prior to the mission, supplies were prepared for 11 of the demonstrations.⁶⁸ Nearly all of the demonstrations were performed on Skylab IV.⁶⁷

The astronauts manning Skylab also performed/attempted 19 experiments/demonstrations that were proposed by high school students. The experiments were part of an effort designed to "stimulate interest in science and technology among high school students" known as the Skylab Student Project.

Originally, 25 student experiments were selected under the program. These experiments, which had been selected from more than 3,400 proposals submitted by boys and girls, were implemented by associating the student investigator with a Skylab principal investigator who then supported the student experimental requirements.⁶⁵ During a preliminary design phase, it was determined that 19 of the selected experiments were suitable for Skylab and they were included in the experiment manifest.⁶⁵ Several of the original 25 student experiments were directly or indirectly related to fluids and materials processing goals and are included in this compilation (e.g., Liquid Motion Studies, Brownian Motion Investigation, Capillary Fluid Motion, etc.)

*After the Ice Melting Demonstration, a globule of water remained attached to a retaining stick. Thus, a third impromptu demonstration was performed when it was suggested that soap, water, and other fluids be added to the drop. This experiment is reported on page 12-27.

4. The Apollo-Soyuz Test Project

Additional opportunities to perform fluids and materials processing experiments were realized in 1975 during the Apollo-Soyuz Test Project (ASTP). From 1972 to 1975, both the U.S. and U.S.S.R were involved in preparations for the mission.

Prior to the mission, a total of 161 ASTP experiment proposals (many of which were related to fluids and materials processing experiments) were submitted to NASA Headquarters from scientists in nine different countries. The experiments were reviewed by the National Academy of Sciences and approximately 30 experiments were selected for inclusion on the mission.⁷⁰

During the historic flight (July 1975), a U.S. Apollo spacecraft docked with a U.S.S.R. Soyuz spacecraft. Throughout the following 2 days, the three astronauts and two cosmonauts performed joint experiments, after which time the Apollo and Soyuz undocked. Apollo remained in orbit 3 days longer in order to complete several additional experiments/demonstrations.^{69,70} Thirteen experiments/demonstrations performed during ASTP were applicable to this data base and are detailed within this document.

It was reported⁵ that although the time to develop experiments was short and resources available for the experiments were more restricted than on Skylab, several ASTP investigators were able to confirm Skylab results and further study fluid phenomena that were observed during previous low-gravity investigations.

V. The Space Transportation System (STS) Employed as a Reduced-Gravity Experimental Facility

1. The Shuttle Vehicle

Approval for the Space Transportation System (U.S. space shuttle) came in 1972 (Reference (71)). Nine years later (April 1981), the first space shuttle (Columbia) was launched from Kennedy Space Center (KSC), Florida. The first two flights of the shuttle were designed primarily to test and evaluate major systems of the shuttle vehicle itself (STS-001 and STS-002) and to perform Earth observation experiments (STS-002). STS-003 carried the first fluids and materials processing experiments performed on the shuttle (e.g., Monodisperse Latex Reactor, Electrophoresis Verification Test). Immediately thereafter, most shuttle flights contained at least one or more experimental payload(s) designed to understand low-gravity fluid/material processes.

Unlike previous Earth-orbiting vehicles, the shuttle can routinely transport research equipment into space and return it to investigators. NASA has implemented several different programs to enable a variety of people to explore worthy research ideas. Thus, experimental investigators have included high school students, college students, fluids and materials processing experts, biomedical personnel, astronomers, Earth observers, IMAX movie makers, etc. Experiments proposed by these investigators can be operated in either a shirtsleeve environment or in an environment exposed to space. Historically, Shuttle orbiting times have varied from 2 days to just over 2 weeks, with low-gravity environments typically varying from 10^{-6} g (steady-state acceleration) to 10^{-2} g (transient accelerations). The nominal altitude for most flights is 160 nmi.⁷²

2. Shuttle Experimentation Selection Procedure

A. Solicited and Unsolicited Proposals

The procedure for placing an experiment onboard the shuttle is detailed in Reference (72). In brief, experiments placed on the shuttle come from many sources including (1) NASA, (2) other U.S. agencies, (3) commercial companies, (4) universities, and (5) foreign government agencies (such as ESA).⁷² NASA-sponsored investigations are often selected from either solicited or unsolicited proposals. Solicited proposals are generated from investigators in response to an Announcement of Opportunity (AO). The AO's typically solicit ideas to achieve a program objective or to study a specific discipline (e.g., reduced-gravity solidification). Nonsolicited proposals include any proposal not related to a NASA solicitation. In addition, NASA occasionally

agrees to support or participate in space research with other U.S. or foreign agencies. In these cases, experiment selection is controlled by a joint agreement between NASA and the agency.⁷² Among other considerations, all proposals are reviewed for (1) scientific and technical merit, (2) payload accommodation requirements (Spacelab facility, middeck experiment, etc.), (3) feasibility of developing flight equipment, (4) availability of flight resources, (5) scheduling and cost, etc. Tentatively selected investigations then typically undergo a thorough science and implementation requirements definition study that results in a plan detailing all phases of the project (including equipment development, operation of the equipment on the shuttle, post-flight data analysis, etc.)⁷².

B. The Shuttle Student Involvement Project

One of the methods for high school students to place experiments on the shuttle was the Shuttle Student Involvement Project (SSIP). From 1982 (STS-003) to 1992 (STS-42), 23 experiments were flown in the shuttle middeck, which had been proposed by high school students.⁷³ Like the Skylab Student Project (detailed above), the experiments were part of program designed to stimulate interest in science and engineering among high school students (grades 9 to 12). The SSIP was a joint venture between NASA and the National Teacher's Association. Under the project, students submitted proposals concerning experiments suitable for flight aboard the shuttle.⁷⁴

Originally, 10 experiments were selected from the first competition in May 1981. Shortly thereafter, 20 more experiments were selected from a second SSIP competition in May 1982 (Reference (74)). Throughout the original SSIP program, there were five such competitions, during which a total of 57 experiments were selected by the National Teacher's Association.⁷³ NASA reviewed the recommended experiments and made the final selection of feasible investigations. These experiments, which had been chosen from thousands of proposals submitted by boys and girls across the U.S., were implemented by pairing each student with a corporate sponsor and a NASA consultant who assisted the student in turning the proposal into a flight-ready experiment.⁷⁴

The experiments were manifested on shuttle missions, and most flew within the next 3 years (1982 to 1985).⁷⁵ However, flight opportunities were not readily available on the shuttle (especially after the Challenger accident in 1986), and many students were out of high school and in college when their experiments were performed.

Although detailed information was not available on 5 of the 23 experiments, it appears that overall, 10 of the 23 experiments performed on the shuttle were directly or indirectly related to fluids and materials processing goals. Seven of these SSIP experiments are included in this compilation; information on the other three were not available at this time and/or were beyond the cut-off date for this publication.

Although SSIP experiments no longer fly on the shuttle, there is a derivative of the program still in existence. This derivative is also called SSIP (although the acronym now stands for Space Science Student Involvement Program). This broader program does not include competitions to place experiments on the shuttle, but instead sponsors five other types of competitions including (1) a future aircraft/spacecraft design competition (grades 3 to 5), (2) an interplanetary art competition (grades 3 to 12), and (3) a Mars scientific experiment proposal competition (9 to 12).⁷⁶

The SSIP competition that most resembles the original SSIP program is entitled "Aerospace Internships" (for grades 9 to 12). This competition requires students to propose experiments that could theoretically be performed at one of several NASA facilities (e.g., the Langley Research Center (LaRC) wind tunnel, the LeRC drop tube, the MSFC Spacelab facility, etc.).⁷⁶ SSIP winners spend a week internship at a NASA research center observing scientists conducting experiments already in progress (their proposed experiment is not conducted).

Additional information on the current SSIP Program can be found at the NASA Office of Human Resources and Education Division (NASA HQ) or the National Science Teachers Association (Arlington, Virginia).

3. Experiment Configuration

Most of the experimentation performed onboard the shuttle occurs in the astronaut middeck area or the payload (cargo) bay.

A. Experiments on the Middeck

The middeck is located directly below the shuttle flight deck and adjacent to the payload bay. The forward and aft sections of the middeck are depicted in figure 15 (Reference (20)). Forty-two storage lockers (typically containing food, clothing, equipment, etc.) can be mounted in the deck. For a given mission, any unused lockers and/or their mounting spaces can be configured with experimental equipment.¹⁹ For some missions, other areas of the middeck are also available for experimental equipment (see Reference (19)). In addition to the "Single" (56 by 53 by 201

cm) or "Double" lockers, experiment apparatus containers (EAC's) can be implemented in the middeck area (figure 16).²⁰ <Note: A derivative of the middeck EAC's are also employed in the payload bay (see pp. 41-42).>

Although the space available for experimentation and power-and-heat rejection capabilities are limited in the middeck, advantages of this location include (1) late access and early recovery of the experimental package, (2) reduced payload integration time and cost, and (3) crew/experiment interaction.

B. Experiments in the Payload Bay

The payload bay, measuring 15 ft in diameter and 60 ft in length, is located between the flight deck/middeck section of the vehicle and the shuttle engines.¹⁹ The bay is used to house a variety of payloads including large experiments, satellites, pressurized Spacelab modules, Get Away Special canisters, etc. Power and heat rejection capabilities of the bay are not as restricted as the middeck area.¹⁹

4. Shuttle Experiment Carriers Which Have Housed Fluids and Materials Processing Experiments in the Payload Bay

NASA has developed a variety of payload carriers to accommodate investigators. These carriers are typically configured in the the exposed cargo bay. Other experiments, which are initially configured in the payload bay, are placed into orbit about the Earth during the mission and picked up either before the space shuttle leaves orbit or by a shuttle which is launched at a later date (free-flyers). On the more sophisticated end of the spectrum of available carriers are the Spacelab experiment module and retrievable free-flyers; on the other end of the spectrum are small self-contained payload canisters (GAS canisters).

A. Pressurized Spacelab Modules

A detailed description of the Spacelab facility is found in References (19, 71, 72, and 77). In brief, Spacelab is a reusable modular facility, configured in the shuttle payload bay. The facility was designed, built, and financed by 10 European nations through ESA.⁷⁷

During a mission, the facility is exposed to space when the cargo bay doors are opened. Basically, Spacelab consists of two elements: (1) an enclosed pressurized laboratory module (which provides a shirt sleeve research environment for the shuttle crew

and accompanying experiments) and (2) unpressurized platforms (pallets) (where equipment such as telescopes, antennas, etc. can be mounted for direct exposure to space and supported with orbiter resources).^{20,71} The total Spacelab power level available is 7 kW.²⁰

Most often, fluids and materials processing experiments have been performed in the pressurized "long" laboratory module. The module is connected to the lower crew compartment (orbiter mid-deck area) via a tunnel adapter and tunnel (the Spacelab Transfer Tunnel)⁷² (see figure 17 (Reference (71))). The module itself is comprised of 9-ft long, 13-ft diameter cylindrical segments made of aluminum alloys and covered with multilayered insulation. Two such segments are employed to create the "long module" (see figure 18, Reference (71)). The first segment (or core segment) contains controls, monitoring equipment, and research experiments. The second segment (or experiment segment) primarily contains research equipment.⁷²

The majority of the equipment in both segments is housed in laboratory racks that line the walls of the module. Up to six double racks and four single racks can be installed in the Spacelab module.¹⁹ The first Spacelab laboratory mission (Spacelab 1) flew on the shuttle in 1983. During this mission and most of the shuttle Spacelab missions (such as Spacelab 3, Spacelab D1, Spacelab D2, Spacelab J, The International Microgravity Laboratory (IML), and The United States Microgravity Laboratory (USML)), a multitude of fluids and materials processing experiments have been performed in this shirt sleeve environment.

B. Small Self-Contained Payloads: Get Away Special Canisters (GAS Cans), MAUS, and Hitchhikers

The STS orbiter payload bay can be used to transport approximately 65,000 lb into Earth orbit. The contents of the bay vary from mission to mission, but for the most part, primary and/or secondary payloads such as satellites, Earth-and-space observation equipment, manned laboratories (Spacelabs), etc., take up most of the available volume in the bay. On average, however, these payloads do not require the entire bay volume and there is sufficient room for additional smaller payloads.⁷⁸

The STS Small Self-Contained Payload (SSCP) program was initiated by NASA to provide individuals and organizations a means of placing a small, (generally scientific) low-cost payload aboard the shuttle on a space-available basis. The NASA GSFC Small Payloads Project (SSPP), which developed and operates the SSCP program, manages two small orbiter bay payload carriers: the Get Away Spe-

cial (GAS) program and the Hitchhiker program.⁷⁹

Details of the GAS program and Hitchhiker program are provided in References (19, 72, and 78 to 81). GAS canisters are standardized aluminum containers that can house small payloads (see figure 19 (Reference (81))). These containers, which are typically configured in the payload bay on a GAS bridge or via some other standard mechanical interface, can be be evacuated or pressurized. The canisters must contain their own electrical power systems, heating/cooling equipment, data acquisition systems, etc. (if required for the stored experimentation), as well as contain limited electrical interfaces that allow simple crew control functions from the orbiter cabin.¹⁹ The payload has only limited crew interaction interfaces; no more than six simple inputs (on/off commands, initiate special sequence, change data rate, etc.) can be performed by the astronauts via the NASA provided relays.⁷⁸

The standard GAS carriers are available in two different sizes: a 5-ft³ volume canister and a 2.5-ft³ volume canister. Users can choose the desired container atmosphere as the internal pressure of the canister can be varied from near-vacuum to approximately 1 atmosphere.⁸¹ Thermal insulation on the bottom and sides of the container provide some thermal protection for the user's payload.

The larger (19.75-in diameter, 28.25-in high) canister can accommodate up to 200 lb of customer equipment; the smaller version can accommodate only 60 to 100 lb of equipment. This equipment, which typically consists of the experiment setup, power source (batteries), sequencing system, and data recording system, is provided by the customer. Often, several experiments are configured into a single canister.

The GAS experiments are divided into three major categories: educational, foreign and commercial, and U.S. Government. In order to assure access to space by a diverse group of users, NASA rotates the GAS flights among the three categories. Within each category, the canisters are flown on a first come, first served basis.⁷⁸

The Hitchhiker carrier, which employs canisters somewhat similar to GAS canisters (although with more complex mechanical and electrical interfaces than the GAS cans), is a modular carrier that is expandable in accordance with payload requirements. Unlike the GAS program, Hitchhiker provides power, data, and command services to the customer's payload. In addition to crew control of the payload, customers at the Hitchhiker control center at GSFC can communicate real-time with the equipment.⁷⁹

The first GAS can to fly on the shuttle was the Getaway Special Flight Verification Payload on STS-003. During this first space

test of the payload, the environment of the canister was evaluated. Since this first flight, over 100 experiments have been flown in GAS or Hitchhiker payloads.

An additional small, cylindrical, self-contained reusable payload carrier called MAUS or Materialwissenschaftliche Autonome Experimente unter Schwerelosigkeit (in English, Autonomous Material Science Experiments in Microgravity) is utilized by the Federal German Ministry for Research and Technology (BMFT).⁵³ The aerospace firm Messerschmitt-Boelkow-Blohm (MBB/ERNO) (Bremen, Germany) developed a standard GAS-Can-type system which is compatible with the interface requirements of the NASA GAS container. Like the GAS canisters, MAUS canisters (1) are configured in the payload bay and are fully autonomous (experiments are initiated and concluded by only a few signals sent by the crew) and (2) house their own power, experiment command and data handling electronics, etc.

C. Free-Flying Satellites Deployed From the Shuttle

C1. The German Shuttle Pallet Satellite (SPAS)

The shuttle pallet satellite (SPAS) was also built by MBB/ERNO and supported by BMFT. The facility, which is a reusable platform designed to operate either inside or outside the cargo bay, can be configured with a variety of commercial and scientific equipment.⁸²

MBB allows customers to fly their experiments on the satellite for a fee. For the initial flight of the satellite, NASA agreed to substantially reduce the charge for launching the facility in exchange for testing the shuttle remote manipulator system's capabilities of deployment and retrieval of the satellite.⁸² (The facility was the first satellite ever deployed and retrieved from the space shuttle during a mission.)

During the STS-007 mission (1983), the facility, which was carried into orbit by the shuttle in the cargo bay, was configured with 10 experiments furnished by BMFT, ESA, and NASA.^{82,83} A (preflight, 1983) diagram of the STS-007 SPAS configuration is represented in figure 20 (Reference (84)). Three of these experiments were related to fluids and materials processing studies. One of these fluids and materials experiments was designed to study heat pipe operation, the others (which were contained in West German MAUS GAS canisters) pertained to the study of Marangoni flow and Mn-Bi solidification. The satellite, complete with experiments, was designated as SPAS-01. Most experiments on the SPAS were designed to operate while the SPAS was in the payload bay; others operated during the short

time (approximately 8 h) that SPAS was deployed as a free-flying satellite.

A description of the SPAS deployment and retrieval is presented in Reference (85). During the mission, the shuttle remote manipulator system (RMS) robot arm placed the 16-by 11-by 5-ft SPAS outside the shuttle cargo bay. Then, after the shuttle maneuvered away from the SPAS (305 m), the SPAS was commanded into free-drift mode (shutting off the platform's altitude control system). During the following 2 h, fluids experimentation was performed that eventually was compared to the earlier experimentation performed with the SPAS configured in the payload bay. Approximately 2 h later, the orbiter was maneuvered back toward the satellite, where SPAS was retrieved by the arm. Later in the mission, the SPAS was again deployed, but for a different purpose. After deployment, the shuttle first maneuvered 21 m away from the satellite and then the rate and control system (RCS) thrusters were fired in the direction of the SPAS to see what effect the blasts would have on the pallet. At this distance, the satellite was "buffeted... [and] at times rolled as much as 90 degrees."⁸⁵ The test was repeated with the shuttle at a distance of 31 and 61 m. Reportedly, the satellite came through the tests "with no ill effects."⁸⁵

After refurbishing, the SPAS facility, now designated as SPAS-01A, was carried into orbit by the shuttle on STS 41-B (1984). (This reflight of the facility reflected the first time a satellite had ever been refurbished and reflown on the shuttle.)⁸³ For this mission, the facility carried a variety of experiments, including two materials processing experiments (reaction kinetics in glasses and slip casting). Both of these experiments were housed in West German MAUS containers. Reference (86) indicated that during the mission the satellite was to (1) be removed from the STS payload bay by the RMS arm, (2) remain attached to the arm throughout the mission (at a position overhead about 5 to 10 ft from the forward payload bay bulkhead), and (3) be replaced in the cargo bay prior to the shuttle's return. However, Reference (83) reported that the "SPAS remained [attached] in the payload bay due to an electrical problem with the RMS." Additional information about the SPAS can be located in References (87 and 88).

C2. LDEF

The Long Duration Exposure Facility (LDEF) was a free-flying cylindrical satellite (30-ft long and 14 ft in diameter) originally housed in the orbiter bay and then placed in Earth orbit by the U.S. space shuttle at an altitude of 257 nmi and an inclination of 28.5° (STS 41-C, 1984).^{89,90} The structure con-

tained 57 science and technology experiments located in trays mounted on the exterior of the structure. (Only four of these experiments were directly related to fluids and/or materials processing.)

LDEF was to be retrieved by another shuttle after approximately 9 months. However, the structure remained in orbit for nearly 6 years because STS flights were delayed following the loss of the space shuttle Challenger. LDEF was eventually retrieved in January 1990 at an altitude of approximately 180 nmi (STS-032).

D. NASA Office of Space Science and Applications Payload (OSTA-2)

A materials processing payload sponsored by the NASA Office of Space Science and Applications (OSTA) was carried on the shuttle during STS-007 (1983). The payload, designated as OSTA-2, was developed by the U.S. and West Germany.⁹¹ Under terms of a cooperative agreement, scientific data obtained from the payload were shared by both countries.⁸²

OSTA-2, which was configured in the payload bay, consisted of two automated experiment facilities. The first, called the materials experiment assembly (MEA) was sponsored by NASA; the second, called Materialwissenschaftliche Autonome Experimente unter Schwerelosigkeit (MAUS) was sponsored by the German Ministry for Research and Technology.⁹¹ <Note: Additional (general) information on MAUS experimental facilities can be reviewed on p. 39.> MEA and MAUS were configured within the shuttle cargo bay on a mission peculiar equipment support structure (MPRESS). The primary function of the MPRESS was to provide mechanical support for the facilities and to elevate "...the MEA package to a height above the level of the cargo bay so that the MEA thermal radiator... [could] dissipate heat from the package into space when the cargo bay doors... [were] open."⁸² The elements of the OSTA-2 payload are depicted in figure 21 (Reference (91)).

D1. The Materials Experiment Assembly (MEA)

MEA was a desk-sized facility, managed by NASA MSFC (see fig. 22, Reference (91)). Three experimental apparatuses, each housed in their own experiment apparatus container (EAC), were configured on the facility: (1) an isothermal furnace, (2) a gradient furnace, and (3) a single-axis acoustic levitator. (Each of these apparatuses had been developed and employed during the SPAR program and were modified for MEA performance.) These three facilities supported the following experiments: (1) vapor crystal growth of semiconductor materials (gradient furnace), (2) melting and solidification of liquid miscibility gap materials (gradient

and isothermal furnaces), and (3) processing of uncontained glass melts (acoustic levitator). In addition to the EAC's, MEA was configured with the thermal, electrical and data subsystems necessary to support the experiment objectives and equipment within the containers. Not only did MEA require a minimum integration interface with the orbiter, but it also required a minimum amount of attention from the shuttle crew.^{82,91}

D2. MAUS (STS-007)

Three automated, MAUS GAS canister-type containers were employed for the West German experiments. Two of the containers were related to an experiment called "The Stability of Metallic Dispersions" and the third container housed equipment related to the study of solidification front physics ("Particle Transport Induced by Directional Solidification").⁸² Each of the cylindrical containers was thermally isolated and had its own service module containing experiment hardware, electrical power equipment, experiment control systems, etc.⁹²

E. MEA-A2

The MEA-A2 facility was flown in the shuttle bay during the Spacelab D1 mission (1985). The same three MEA-A1 experimental apparatuses were configured on MEA-A2.⁹³ These apparatuses now supported five experiments: (1) the vapor crystal growth of semiconductor materials (gradient furnace), (2) the directional solidification of PbSnTe (gradient furnace), (3) the melting and solidification of liquid miscibility gap materials (isothermal furnace), (4) the diffusion of lead and zinc (isothermal furnace) and (5) processing of uncontained glass melts (acoustic levitator). (Similar MAUS experimentation was not associated with this MEA payload.)

F. The Materials Science Laboratory (MSL) and the United States Microgravity Payload (USMP)

A third MEA facility was planned, although canceled prior to flight.⁹⁴ Before its cancellation, the facility was to fly on what was designated as the Materials Science Laboratory-1 (MSL-1) mission.⁹⁴ (Later, the MSL acronym became associated with the materials science laboratory (MSL) experiment carrier.) Although Reference (82) indicated that at least five MSL flights were scheduled to fly on the shuttle, only one MSL payload actually flew on the orbiter (MSL-2).

While the MEA facilities had been basically self-contained payloads operating independently of the shuttle, the MSL payloads were designed to use resources provided by the orbiter (orbiter power, orbiter heat exchanger, etc.).^{16,95} Power levels of 470 W could be continuously provided.²⁰

The MSL was designed to be a reusable, standard, materials processing experiment carrier. A maximum of three experiments (each contained in an experiment apparatus container, and each weighing a maximum of 308 kg) could be accommodated on the structure.²⁰ In addition to providing structural support to experiments (via a MPES platform), this standard carrier was also configured with (1) "standard" subsystems that provided environmental control, power control, command and data management, etc., and (2) appropriate orbiter interfaces (power and heat exchange as mentioned above as well as interfaces for crew commands to the facility).^{94,95} It was intended that the standard subsystems support a variety of experiments configured on the facility during the MSL flight history.

MSL-2, which flew on the shuttle in 1986 (STS 61-C), is depicted in figure 23 (Reference (95)). In addition to the standard equipment housed on the MSL (as detailed above), the facility also contained experimental equipment directly related to three different materials processing investigations (an automated directional solidification furnace, an electromagnetic levitator, and a three-axis acoustic levitator.)

MSL-2 flew on the shuttle just prior to the explosion of STS 51-L (Challenger) in January 1986. During the months immediately following the disaster, the backlog of experiments that were to fly on MSL grew. Thus, a new (and improved) derivative of the MSL experiment carrier was designed that could support additional materials processing investigations.⁹⁴ This new experiment carrier, which is currently manifested on shuttle missions, is called USMP. In addition to accommodating twice as many investigations as the MSL, the USMP (1) can provide more resources to each experiment (the facility can be allocated up to 50 percent of the total orbiter resources available for payloads) and (2) has improved data handling and command capabilities (including real-time command and data analysis capabilities by investigators on the ground).⁹⁶ The facility, which employs two MPESs mounted adjacent to each other, spans the width of the orbiter. USMP subsystems, mounted on the forward MPES, provide resources to the science experiments (fig. 24).⁹⁶ Experiment hardware is mounted on the tops and sides of each MPES (e.g., figure 25).⁹⁶

The first USMP, designated as USMP-1, flew on the shuttle in 1992; USMP-2 was flown in 1994. Several additional USMP flights are planned. (Additional information on the USMP can be located

in References (96 and 102).)

G. Other Current Carriers

Recently (post-1989), additional carriers have been employed to place experiments on the shuttle (i.e., Spacehab, and the European Retrievable Carrier (Eureca))

Detailed descriptions of these carriers are not presented here as this hardcopy version of the data does not contain summaries of these recent experiments.

VI. The Need for a Data base

1. Creation of a Data Base to Highlight Low-Gravity Fluid Response

NASA MSFC has played a major role in low-gravity fluids and materials processing investigations throughout its history. Principal- and/or co-investigators from MSFC have proposed, designed, and implemented numerous experiments on almost every type of low-gravity terrestrial and extra-terrestrial facility described in the previous sections. A small sampling of MSFC past experiment involvement is represented in table 2. In addition, MSFC personnel are currently heavily involved in STS mission science and experiment implementation.

Table 2

MSFC Investigator	Mission	Experiment
Bannister	Apollo	Heat Flow and Convection
Baugher	STS	Acceleration Measurement
Carter	STS	Protein Crystal Growth
Darbro	Skylab	Liquid Films
Facemire	Skylab	Diffusion
Johnston-McCay	SPAR	Alloy Solidification
Kornfeld	STS	Monodisperse Latex Reactor
Kroes	STS	Fluid Experiment System
Lacy	Skylab	Immiscible Liquids
Lacy	ASTP	Synthetic Alloys
Lee	STS	Crystals in Aqueous Soln.
Lehoczky	STS	Crystal Growth
McKannan	Apollo	Electrophoresis
Poorman	Skylab	Metals Melting
Schafer	SPAR	Liquid Mixing
Snyder	Apollo, STS	Electrophoresis
Snyder	STS	Electrohydrodynamics
Vaughan	Skylab	Water Drop Dynamics
Vaughan	Skylab	Acoustic Positioning
Whitaker	ASTP	Capillary Wicking
Whitaker	STS	Tribology
Williams	Skylab	Brazing
Yates	Apollo	Composite Casting

Bob Naumann (a former MSFC scientist), took a detailed look at many early low-gravity fluids and materials processing experiments and summarized what scientists and engineers had discovered in several areas of reduced-gravity research. In Naumann's 1980 book entitled "Materials Processing in Space: Early Experiments" (Reference (5)), for example, significant findings in the area of crystal growth, metallurgy, and fluid phenomena were related. While it was reported that in many cases, experimenters observed expected results, often times there were also a number of "surprises," some of which were thought to be of significant scientific value. Specifically, he noted that "In the area of fluid phenomena there appears to be considerable confusing data, indicating that there is still much to be learned about the behavior of fluid in a low-gravity environment."

MSFC scientist Charles Schafer performed experiments on the SPAR sounding rocket in 1975 and 1976, which were specifically designed to determine the effect of the vehicle's acceleration on pure diffusive mixing.⁹⁷ The experiment, which involved the melting and solidification of three cylindrical samples during the low-gravity phase of the rocket, illustrated that pure diffusive mixing between a section of pure indium joined to a section of indium-lead was not observed, but rather the magnitudes of convective flow experienced in the samples were related to the vehicle's acceleration environment. Today, many scientists attribute unwanted or unanticipated convective flow fields observed during reduced-gravity investigations to the vehicle's (low-gravity) acceleration environment.

A significant review of both early experimental results and more recent investigative efforts indicate that fluid characteristics have rarely been systematically examined over several missions. While a single investigator may have performed experiments in a logical way changing only one or two variables (such as Schafer), in most cases, analysis of the contribution of each variable to the resulting fluid response has not been realized. Not only have most past experiments been significantly complex (involving several fluid dynamic parameters), but associated investigators (within the same research area) have rarely employed the same sample materials, thermal and solutal gradients, crucible materials, etc. As a result, in only a few instances has low-gravity fluid response appeared to be sufficiently understood to confidently exploit the benefits into profitable space processing ventures. Particular investigators have realized major successes in terms of using reduced gravity to achieve particular objectives, but few have returned with (1) space processed materials that were significantly superior to those produced on Earth, or (2) sufficient experimental evidence to support definitive flow theories.

Because it was recognized that many aspects of fluid response in the low-gravity environment were still not well understood by the scientific community as whole, and that vehicle accelerations may play a significant part in the results achieved by experiments, scientists at MSFC wanted to create a data base that was designed to highlight the basic fluid flow processes that govern most low-gravity fluids experiments. It was surmised that once these flow processes were better understood, space experiments and computational models could be designed to more accurately exploit and predict space fluid dynamics. It was clear, that to better understand the fluid dynamics governing each of these systems, the objectives, setup, inflight procedure, and results of these investigations had to be determined and studied. Thus, work related to identifying and cataloging information related to past experiments was initiated.

Within several months, nearly 500 fluids and materials experiments (all of which had previously been performed in sounding rockets or orbiting manned spacecraft) were identified. Soon thereafter, outline information about each investigation was placed into a data base.

2. Creation of a Historical Experimental Record to Serve Scientists Worldwide

Although it was originally planned that the data base would be used as an in-house tool to help highlight governing flow processes, requests for information from the MSFC-housed base came weekly after news of the data base and its contents became publicized. Personnel requesting information were not interested in using the data base to understand flow processes, rather they were intent on locating information on experiments previously performed in their particular research area. The first of these requests came long before most of the objectives, setup, inflight procedure, and results of these 500 experiments had been discerned and documented in detail in the data base.

Scientists and engineers continually sought information from the MSFC data base because such a similar compilation of these reduced-gravity experiments was not available elsewhere. Without such a catalog, interested science communities could not begin to comprehend the vast number of experimental objectives, parameters, conditions, etc., that had already been analyzed in terrestrial and extra-terrestrial low-gravity facilities. Although some investigators that were already active in the low-gravity experimental community were aware of past and current research/proposals in their specific area of interest, new (or would-be) investigators outside this community had very limited knowledge of these experimental efforts. The lack of historical

scientific record made it difficult for new investigators to propose up-to-date, valuable research (especially studies related to significant understanding of fluid phenomena), although they had formulated innovative experimental objectives.

In addition, while it was imperative that all scientists proposing new space research understood lessons learned in the past, many researchers remained unaware of the number of low-gravity experiments that had been completed in their subject area. One GAS can investigator, whose experimental equipment had already been delivered to NASA KSC for implementation into the shuttle, thought his foaming experiment was the first to fly on such a vehicle.⁹⁸ He was surprised to learn that several such experiments had been performed previously in a reduced-gravity environment.

It soon became clear to both MSFC and NASA-Headquarters management that there was a great need for a historical compilation of the experiments accessible to researchers worldwide. An electronic data base cataloging these experiments would provide an invaluable source of information on low-gravity investigations that could later be employed to highlight important flow processes. The data base would not only serve current and future experiment proposers, but would also be an invaluable educational tool for universities and other institutions interested in low-gravity science issues. The compilation would also provide a historical record of low-gravity initiatives.

Thus, despite the importance of an in-house study to examine earlier investigations and determine the contribution of low-gravity fluid phenomena, completion of information related to each of the experimental investigations became the immediate goal. Once this information was assembled and the data base was available on-line and in hardcopy format, the authors could then compare, analyze, and evaluate the roles of flow parameters and governing fluid physics in experimental systems.

Still, in an effort to identify and tag the governing fluid dynamics for each of these experiments (for this later study and for on-line or hardcopy data base use), an extended key words section (which included fluid characteristics) was prepared for each of the investigations. It was hoped that via these key words, data base users would search for other experiments that had similar fluid dynamics challenges. It was recognized that while many of the experiments appeared to be vastly different from one another in terms of basic research area (solidification of melts, protein crystal growth, vapor diffusion, electrophoresis, etc.) they were driven by similar flow properties (e.g., convection, diffusion). Thus, it seemed critical that investigators became aware not only of research efforts

in their major area of interest, but also of seemingly unrelated scientific endeavors that were similar in terms of governing fluid dynamic phenomena.

3. Identifying Past Experiments/Limiting the Scope of the Data Base

When work on the data base was initiated in 1986, its authors were unaware that hundreds of fluids and materials processing experiments had already been performed in terrestrial and extraterrestrial low-gravity environments. Merely identifying (a) the titles of all past experimental efforts and (b) the principal investigators associated with these experiments was a significant task.

While experiment/investigator lists for some carriers were fairly well documented (SPAR, Consort, MASER, Skylab, and ASTP), similar lists for other carriers/low-gravity facilities proved harder to find. For example, there were no composite lists of experiments performed in the KC-135 aircraft, the MSFC or LeRC drop towers, the Mercury and Apollo Spacecraft, the Aerobee and TT-500A sounding rockets, and the Space Transportation System. Thus, a massive search to identify these individual past efforts was initiated. Hosts of historical and flight-related documents were scoured for payload/investigator listings.

Because the number of terrestrial and extra-terrestrial experimental efforts performed to date (then 1986) topped 700, it was determined that the scope of the data base had to be limited to some degree to insure completion of a good compilation. Thus, although terrestrial low-gravity experimental efforts were viewed as extremely important, it was determined that only experiments that experienced more than 4 min of reduced gravity experimental time would be considered for the data base. This decision (to omit terrestrial reduced-gravity research efforts performed in laboratory, drop tower, drop tube, and low-gravity aircraft facilities) stemmed not only from the large number of longer-duration investigations that had already been performed, but also from the difficulty in finding listings and further information on the past terrestrial experiments.

During the early days of the data base compilation effort, information was gathered on all the (then previous) reduced gravity experimentation performed on (1) U.S. manned space vehicles, (2) payloads deployed from U.S. manned space vehicles, and (3) sounding rockets (excluding Soviet and Chinese programs). After these experiments were identified and outline information about each placed in the data base, in-depth searches for additional data on each of the investigations began. Based on these

searches, information concerning these pre-1987 investigations was continually upgraded and refined.

Simultaneously, outline information on new investigations (performed after 1986) was entered in the data base as low-gravity flights were completed. Each of these newer outlines could not be significantly expanded until long after their associated low-gravity experiment flight date (as detailed (published) postflight information typically did not become available for 1 or 2 years).

When it was later decided (1988) that a complete historical record of past experimental initiatives should be published in electronic and hardcopy formats, the following was recognized:

(1) Experiment descriptive data describing each of the 600 investigations then contained in the compilation had to be expanded past the outline information stage to include detailed experiment summaries.

(2) Entry and expansion of data related to new low-gravity initiatives had to be curtailed in order to complete the detailed summaries described in (1). Thus, only outline information about new experiments would be entered into an electronic version of the data base until the first hardcopy release of the initial 600 experiments was available.

4. Types of Experiments Selected for Data Base Inclusion

Experiment types selected for data base inclusion extended from basic fluid flow examinations to complex materials science initiatives. **The goal was to include all carry-on (manifested) EXPERIMENTS (affected by low-gravity fluid physics) which were performed (1) on U.S. manned space vehicles, (2) on payloads deployed from U.S. manned space vehicles, and (3) on sounding rockets (excluding the Chinese and the (former) Soviet programs).** These experiments included (a) initiatives that were performed primarily to examine low-gravity fluid statics and dynamics (including experiments that sought to explain fluid flow theories), (b) initiatives that were performed to examine flow processes related to biotechnology or materials processing, and (c) all materials processing experiments. Historically, most of these experiments had been performed to explore beneficial flow fields expected in the reduced-gravity environment.

Major titles of research suitable for inclusion in the data base were as follows:

Bioprocessing/Biological Experiments
Capillarity
Combustion
Composites with Gases
Composites with Solid Particles
Critical Point Phenomena
Containerless Processing
Crystal Growth from Solution
Crystal Growth from the Melt
Crystal Growth from the Vapor
Diffusion
Fluid Physics
Liquid Phase Sintering
Metals and Alloys
Physical Chemistry/Phase Transition
Protein Crystal Growth
Systems Exhibiting a Miscibility Gap
Technological Experiments

5. Types of Experiments Not Considered for Data Base Inclusion

As stated above, although terrestrial low-gravity experimental efforts were viewed as extremely important, only experiments that experienced more than 4 min of reduced-gravity experimental time were considered for the data base. In addition, fluid analyses and/or fluids experiments related to the successful operation of (1) the low-gravity vehicle itself (propulsion systems) or (2) the housekeeping equipment/facilities employed on the vehicle were not considered for inclusion in the data base. Although the operation of these vehicle systems was dependent on reduced-gravity fluid phenomena, they were rarely considered "experimental payloads."

Typically, experiments/analyses pertaining to the following were not entered into the data base: (1) ground-based (1-g) laboratory investigations performed in preparation for a sounding rocket or manned spacecraft experiment; (2) ground-based reduced-gravity efforts performed in laboratories, aircraft, drop towers, and drop tubes; (3) experiments performed on suborbital vehicles directly related to heat pipe development; (4) experiments performed on an orbital or suborbital vehicle designed to determine the operation of that or another low-gravity vehicle during lift-off, free fall, orbit or re-entry (e.g. sloshing of vehicle's fuel tanks, fluid distribution at the vehicle's propulsion intake pump, etc.; this includes Aerobee sounding rocket experiments); or (5) analyses of major housekeeping systems or experimental facilities that employ fluid processes (e.g., waste management facilities, vehicle cooling/air loop, fluid/thermal distribution of materials processing furnaces, etc.).

6. Missions Encompassed and Detailed in this Technical Memorandum

This technical memorandum contains the first hardcopy release of the data base and details the nearly 600 experiments performed during the programs listed in table 3.

Table 3

Experiments detailed in this technical memorandum were performed:

- (1) Throughout the duration of the Mercury, Apollo, Skylab, and Apollo-Soyuz missions (1962-1975)
 - (2) Throughout the duration of the Space Processing Applications Rocket (SPAR) program (1975-1983)
 - (3) During the German sounding rocket program up to TEXUS 18 (1977-1988)
 - (4) Throughout the duration of the Japanese TT-500A program (1980-1983)
 - (5) During STS program through STS-32 (1982-January 1990)
 - (6) During the Consort sounding rocket program prior to Consort 2 (1989)
 - (7) During the Swedish MASER program through MASER 2 (1987-1988).
-

A summary of the experiment types detailed within this technical memorandum is presented in table 4.

 Table 4
 Experiment Types Within this Technical Memorandum

Program	Number of Experiments
Mercury and Apollo*	11
Skylab	46
Apollo-Soyuz Test Project	13
U.S. Space Shuttle	227
Spacelab Missions	
Spacelab 1 (1983)	36
Spacelab 2 (1985)	3
Spacelab 3 (1985)	5
Spacelab D1 (1985)	49
Middeck	50
Payload Bay**	84
Sounding Rocket Programs	
U.S. SPAR	46
German TEXUS	193
Japanese TT-500A	14
Swedish MASER	15
U.S. Consort	23
	588

* The only missions which appear to have had such experiments were Mercury-Aurora 7, and Apollo 14, 16, and 17.

**Excluding Spacelab Missions, but including (1) GAS Cans and MAUS cans, (2) Payload Bay Carrier Systems (e.g., MEA and MSL), (3) Free Flying Satellites deployed from the Payload Bay (e.g., LDEF and SPAS).

7. Data Sources

The majority of the information in the data base was extracted from publications that detailed experimental information. Most of these publications were located via electronic literature searches using the NASA Research Connection (ReCon) system at the Redstone Scientific Information Center, Huntsville, Alabama.

Because principal and co-investigators were typically the authors of published information describing experiment objectives and postflight results, identification of these key personnel was critical. Once associated investigator(s) were identified, their

names were entered into the ReCon system and author searches were performed. Each of these searches resulted in an electronic listing of papers (with abstracts) authored by the investigator. After the abstracts were read, publications applicable to low-gravity research were obtained from the library. Later, these publications were studied and detailed information concerning past experiments was entered into the data base. All in all, over 500 such author searches were performed, resulting in the review of thousands of abstracts and documents.

Although much of the general information about each of the experiments could be located in published documents (typically experimental objective, payload type, processing facility, mission, and mission date), these information sources often did not specifically contain data such as co-investigators, materials processed in the low-gravity environment, builder of the processing facility, details of experimental results, etc. Often times, even distinctions between ground-based and low-gravity experiments were difficult to discern from available publications.

In addition, information related to specific classes of experiments proved particularly difficult to obtain. For example, several times, significant details concerning STS GAS can experiments could not be attained. The major reasons for the lack of reported GAS details were (1) several GAS can experiments were privately funded and the users were not required to document results, (2) a significant number of GAS can experiments failed and investigators did not wish to document these difficulties, (3) most GAS investigators realized that they had one and only one shuttle flight opportunity and thus did not have to illustrate by their reported results that they merited additional flight opportunities, and (4) many GAS can investigative teams involved high school or college students who were (a) not accustomed to publishing papers related to scientific research or (b) graduated prior to the launch of their payloads and then did not write postflight reports.

Because a significant amount of data could not be discerned for several of the low-gravity experiments, investigator input and review of information was sought to (1) help fill in missing information related to several data fields and (2) insure accuracy in reporting information.

8. Querying Investigators

The Center for Space and Advanced Technology (CSAT), Huntsville, Alabama, was contracted to help with this query of experiment investigators. The primary objective of the three-person CSAT task force was to place the (electronic) data base information into

hardcopy questionnaires for review by investigators.⁹⁹ To achieve this task, both CSAT and the only NASA engineer working on the project (1) reviewed experimental information already in the data base, (2) acquired multiple experiment-related publications pertaining to the experiments, (3) amended experiment records adding some missing information into the records that was required before query sendout (excluding experiment summaries), (4) formulated specific questions for investigators asking them to clarify confusing items presented in available publications, (5) contacted investigators via phone to obtain basic information such as current address, materials processed, etc., and (6) reformatted the electronic data base records into mailable questionnaires for the investigators.

Via these queries, one or more of the suspected principal investigators for each experiment was/were contacted by mail and asked to (1) assess the accuracy of the existing data base information on their experiment; (2) make additions where information was unclear and/or missing; (3) write an short (18 line) experiment summary describing the objectives, setup, and results of the low-gravity investigation; and (4) send publications which described the low-gravity investigation.

Over 600 of these queries (at least one for each experiment in the data base) were mailed by CSAT to nearly 300 investigators worldwide (several of the 600 experiments in the data base had the same principal investigator). "Simply" locating the current address of nearly 300 principal investigators, was in itself, a significant task.

Items sent in the mailings to investigators consisted of the CSAT cover letter (included in the appendix to this introduction), a typical investigator questionnaire, and a sample of what a data base entry was expected to look like. CSAT kept a log of the number of questionnaires sent, date mailed, date of reply receipt, and number of queries returned.

From this initial query to investigators, approximately 40 percent of the 600 experiments were reviewed to some degree and returned (less than 1 percent of the summaries were sent back marked "Returned to Sender"). The majority of the queries returned by the investigators included one or more of the following: (1) identifications of additional principal and co-Investigators, (2) minor changes/additions to the original information sent to the investigators, and/or (3) identification of additional publications that described the research. Only approximately 60 of the 600 queries were returned with the requested experiment summary describing experimental objectives, setup, and results, and of these, approximately 30 were written well enough to sufficiently describe the experiment. Often

times, handwriting of the investigators was difficult to read, or the English responses from foreign investigators were difficult to decipher.

9. Procuring Documents to Allow Preparation of Experiment Summaries

After inputting the information provided via the investigator responses into the data base, it was clear that over 500 experiment summaries had to be prepared based on available documentation describing each experiment. Although initially, CSAT had written 40 short (18 lines or less) experiment summaries, it was decided that experiment descriptions would be more effective if they were much longer and more descriptive. As a result of this decision, these 40 CSAT summaries were eventually rewritten.

In order to write these detailed experiment summaries, extreme efforts were made to procure every experiment-descriptive document pertaining to each investigation in the data base. Among these documents were several experiment-related articles that had been published in a foreign language. In many cases, these articles were translated for use in the experiment summaries (especially if insufficient information on the experiment was available in English). Not all non-English documents could be translated in the interest of time (re: timely release of this TM and on-line versions of the data base).

Although some investigators via their response had identified additional references describing the experiment, most did not send copies of these documents (although asked to do so). Often these references proved to be highly obscure (in-house reports, contractor reports, conference poster sessions, non-English publications, etc.) and could not be attained. Thus, several key publications could not be attained prior to the release of this technical memorandum.

10. Preparing Meaningful and Complete Experiment Summaries

After the CSAT contract had ended, a two-man task force from Wyle Laboratories was contracted to aid in the preparation of these summaries. This new contractor effort was funded via the MSFC Commercial Projects Office (PS05). (PS05 was aware of the data base and wanted to see the experiment summaries completed in a timely manner.) One of the Wyle contractors searched for experiment-descriptive documents; the other (J. Jones) aided the only NASA engineer working on the project (C. Winter) in the writing of the 500+ experiment summaries.

Identifying missing information related to each of the data fields and writing the remaining experiment summaries proved to be a gigantic task. Hours, months, and years of studying experimental reports, newspaper articles, journal articles, etc. were required to fill in the missing descriptions of each of the individual data fields. To achieve these ends, Winter and Jones (the authors of this TM) read and summarized information from over 2,000 sources. Most often, the length and detail of the resulting experiment summary was directly related to the amount of descriptive information published about the investigation.

Experiment summaries were written with the several goals in mind:

First, the experiment summary was written such that the average reader could understand the objectives and direction of the scientific research without being a specialist in that research field. To achieve this goal, the summaries most often began with background information on the scientific area being investigated (for example, explaining (a) what electrophoresis is and its importance, (b) why foamed metals are considered valuable, (c) why the reduced-gravity environment should aid in the study of critical point phenomenon, etc.).

Second, every attempt was made to identify experiments that were performed in a series by an investigator or group of investigators (i.e., results from an earlier experiment in the series were used to define objectives/experimental parameters for later experiments in the series). This was done to insure that the logical progression of the overall research effort could be followed by the user. (It should be noted however, that identifying a series of experiments was often difficult because the (1) principal investigator(s) throughout the series were different, (2) there was no mention in applicable literature as to a research progression, and/or (3) later experiments did not appear applicable to the initial investigations.)

Third, great efforts were made to insure that experimental objectives, setup, inflight procedure, and results were clearly reported (especially since pictures and graphs of the experiment/associated data would not be available in early releases of the information). To understand and report these experiment details, every publication collected concerning an experiment was consulted for input into an experiment summary. Specifically, significant results were highlighted in terms of fluid dynamic phenomena where possible.

Fourth, when preparing the descriptive summaries, experimental success in terms of planned objectives were highlighted, rather than experiment failures. However, experiment anomalies were briefly detailed when investigative results were significantly

affected by these problems.

Fifth, information that was difficult to understand was often quoted directly from the source. Quotes were also used to highlight major experimental results, report critical information related to the experiment, identify experiment anomalies, or to simply re-state information as provided in available sources.

Sixth, notes from the author of the experiment summary were included to help the data base user understand a variety of items concerning the experiment. Often these notes indicated that available information was (1) conflicting with other sources, (2) difficult to understand, (3) did not follow a logical path, (4) not published in English, or (5) not received prior to the release of the TM.

Seventh, although many investigators were contacted by phone to initially obtain outline information (such as current mailing addresses, principal investigator designations, etc.) and several verbally detailed experiment anomalies and other information, experiment summaries were generally not written based on this "word of mouth" information. Great efforts were made to use published documents to describe the experiments and any associated difficulties.

11. A Second Query to the Investigators

After all the experiment summaries were prepared, information available on each investigation was once again sent to at least one of the identified investigators. This time, approximately 600 principal and/or co-investigators were contacted for their input and evaluation. This second query was done (1) to insure all research efforts were accurately represented in the data base, and (2) to give investigators a second chance to review the information within the data base before it was published and electronically placed on-line. Samples of items sent in the mailings to investigators are in the appendix to this introduction. These items included the Wyle cover letter and a typical investigator experiment summary complete with an "Additional Questions" section.

Response from the investigators was better than expected, especially since they had been told that if no response was received, it would be assumed that the experiment summaries were correct as written. (The investigators were given a fixed amount of time in which to respond with corrections and/or additions to their experiment record. In addition, they were informed that if no response was received from them in this period of time, the information in each of their records would be assumed to be cor-

rect.)

Approximately 50 percent of the experiment summaries were evaluated and returned by the Investigators. The investigator input was invaluable as in some cases unknown Co-investigators were identified, unpublished experimental results were detailed, etc. Although it was clear that almost all of the returned experiment summaries had been read thoroughly (as was evident from slight corrections made throughout the body of the summaries), very few editorial changes/additions were made by the investigators, thereby indicating that the quality and content of the summaries were acceptable and accurate. Several positive comments were received from investigators; only one of the 600 expressed that he was somewhat dissatisfied with the summary of his experiment (although this investigator did not rewrite the displeasing sections). The summary was carefully rewritten to reflect his comments.

Although many investigators cited several new information sources concerning their experiments, not all of these data sources could be attained in a timely manner (prior to the release of this TM). However, nearly all sources of information cited by investigators were added to the "References/Applicable Publications" field of each experiment entry.

12. Data Base Format

The MSFC-designed data base format has changed slightly over the years, as need and interest of users dictated. The basic design, however, has remained the same and presents all information describing a single low-gravity experiment in a single data base record. In general, the data base contains a separate record for each flight of an experimental investigation. An example of one record from the data base is presented on the next page. (The summary has been severely abridged to fit within the confines of a single page.)

Each record has 18 separate data fields. These fields are highlighted by the **bold-face** type in the example and contain a variety of information such as principal and co-investigators, mission, experiment name, key words, etc.

Example of One Experiment Record in the Data Base

Principal Investigator(s): Hart, J. E. (1)
Co-Investigator(s): Toomre, J. (2), Gilman, P. (3),...
Affiliation(s): (1) Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado, Boulder, (2)...

Experiment Origin: USA
Mission: STS Launch #17, STS-024 (STS 51-B, Spacelab 3...
Launch Date/Expt. Date: April 1985
Launched From: NASA Kennedy Space Center, Florida
Payload Type: STS Spacelab Facility, Spacelab Rack
Processing Facility: Geophysical Fluid Flow Cell (GFFC)
Builder of Processing Facility: Aerojet, Azusa, California

Experiment:
Geophysical Fluid Flow Cell (GFFC)

... The specific objective of this Spacelab 3 experiment was to study the interaction of rotation and convection similar to that which occurs in the atmosphere of a rotating planet like Earth or Jupiter....

Key Words: Fluid Physics, Contained Fluids, Spinning Containers, Rotating Atmospheres, Rotating Fluids...

Number of Samples: one hemispherical shell
Sample Materials: silicone oil (0.65 centistoke viscosity)
Container Materials: inner shell fabricated from polished nickel; outer shell fabricated from transparent sapphire...

Experiment/Material Applications:
Simulation of planetary atmospheres is achieved by producing rotating, spherical convective flows with effectively radial gravity fields induced by dielectric polarization forces.

References/Applicable Publications:
(1) Hart, J. E., Glatzmaier, G. A., and Toomre, J.: Space-Laboratory and Numerical Simulations of Thermal Convection in a Rotating Hemispherical Shell with Radial Gravity. Journal of Fluid Mechanics, Vol. 173, 1986, pp. 519-544. (post-flight results)...

Contact(s):
Dr. John E. Hart
Department of Astrophysical Planetary and Atmospheric Sciences
Campus Box 391
University of Colorado
Boulder, CO 80309

A listing of all of the field names (and associated field contents) is presented below:

<u>Field Name</u>	<u>Field Contents</u>
Principal Investigator(s)	Name(s) of principal investigator(s)
Co-Investigator(s)	Name(s) of co-investigator(s)
Affiliation(s)	Principal- and co-investigator(s) (1) affiliation(s) (institution or company) both at the time of the flight experiment and currently (if different) and (2) location(s) of the named affiliation(s)
Experiment Origin	Country from which the experiment originated
Mission	Specific mission on which the experiment was performed
Launch Date/Expt. Date	(1) Month and year of vehicle launch or (2) experiment date (Skylab only)
Launched From	Vehicle launch location
Payload Type	Type of experimental payload (e.g., sounding rocket, STS Spacelab, STS GAS canister)
Processing Facility	Name (and possibly) brief description of experimental hardware
Builder of Processing Facility	Name and location of the builder of the experimental hardware
Experiment	Experiment summary which includes (1) the experiment name, (2) the experiment number (if applicable), and (3) a description of experiment objectives, setup, and results
Key Words	List of subject titles associated with the experiment/research

Number of Samples	Number of samples employed during the low-gravity experiment
Sample Materials	List of employed sample materials
Container Materials	List of employed container materials
Experiment/Material Application	Brief discussion of (a) the usefulness/application of the sample material and/or experimental process or (b) the reason(s) low-gravity research was warranted.
References/Applicable Publications	List of identified references describing (1) the low-gravity experiment, (2) the employed processing facility, or (3) other related work (i.e, ground-based experiments performed in preparation for the flight, directly associated mathematical analyses, etc.)
Contacts	Name(s) and work address(es) of investigator(s) or other contact(s) associated with the experiment

The major portion of each record is contained within the experiment field. As detailed on pp. 56-58, the field usually includes (1) a short background describing the 1-g constraints on the system of interest, (2) a statement of the experiment objective(s), (3) a description of the processing facility and inflight experimental procedures, and (4) a discussion of the results. If the experiment was one in a series of low-gravity investigations, then a statement to this effect is also included in the summary as well as a list of previous experiments in the series. This assures that the logical progression of the research effort is identified.

For each of the nearly 600 investigations contained in this TM, great effort was made to insure that information applicable to each of the 18 data fields was documented.

13. Quantity of Data Available in Each Experiment Record

Because most of the compiled data is a result of information gathered from open literature and investigator response, the

clarity of the information as it relates to experimental objectives, setup, inflight procedure, and results depends greatly on the amount of available documentation of the experiment and the amount of investigator input.

14. Categorizing the Experiments Within the Data Base

Categorization of the experiments within the data base (i.e., the separation of the 600 experiments into chapters for this technical memorandum) was difficult to do. It was not clear if categorization criteria should be (1) like boundary conditions (e.g., free surface systems, contained systems), (2) suspected dominating flow processes (e.g. Marangoni flow, convection related to vehicle acceleration), (3) scientific objective (e.g. crystallization, pure diffusion, liquid stability), (4) observed undesirable low-gravity flow characteristic (e.g., poor mixing, electroosmotic flow, deleterious capillary flow), (5) research area (bioprocessing, vapor crystal growth, protein crystal growth), or (6) some combination of the five.

For example, several experiments had been performed in the space environment to study the flow processes governing the production of crystals using a floating zone. Not only do the thermal and solutal gradients in this system play a major role in the resulting solidified crystal, but the free surface of the zone introduces Marangoni forces, and the suspended molten section of the zone is susceptible to gravitational accelerations. Thus, it was difficult to discern if this experiment should be categorized with (1) all free surface experiments (with and without thermal and/or solutal gradients), (2) all experiments which should be governed by Marangoni flow, (3) all float zone crystallization experiments, (4) all experiments affected by either (a) unwanted capillary flow or (b) residual acceleration effects, (5) all experiments involving crystal growth from the melt, or (6) some combination of these criteria.

After much consideration, it seemed reasonable that the categorization criteria should be selected based on past database-user information requests.

15. Past Requests for Information In the Data Base

Many requests for information in the data base had already been fielded by its authors, and the requests were as varied as the experiments themselves. While the majority of people asked for listings of experiments in a certain research area (i.e., solution crystal growth, vapor crystal growth, metallic foaming, etc.), a significant number of requests were made for lists of fluid systems which exhibited a particular (undesirable) flow

characteristic (i.e., (a) poor mixing, (b) unwanted bubbles, (c) unexpected agglomeration, and (d) undesirable liquid configuration).

Categorization of experiments by either desirable or undesirable flow characteristics (instead of similar research area) would be extremely interesting for the purposes of understanding low-gravity fluid phenomena, but would hamper most data base users searching for information in a particular research area. For example, a listing of fluid systems that exhibited an undesirable low-gravity configuration would include (but not be limited to) (a) insufficient wetting of a melt to a crucible, (b) insufficient fluid positioning at an inlet port during fluid transfer, and (c) lack of liquid anchoring to disks that contain a liquid bridge. Although these particular experimental systems are mainly dependent on reduced-gravity capillary flow and wetting conditions, they clearly do not belong to the same scientific discipline (represented are solidification of alloys, fluid transfer, and liquid bridge creation).

Because the majority of previous requests for information had been for experiments categorized by research area, this criteria was used to formulate the chapters of this TM. However, although desirable and undesirable fluid characteristics related to each of the experiments were not used as the main categorization criteria, they are detailed in the accompanying key words data fields. In addition, boundary conditions, suspected dominating flow processes, scientific objectives, and even the categories themselves are listed in this key words section. Because this hardcopy version has an extensive key words index, experiments with like flow characteristics can be identified in this document.

VII. The Hardcopy Version of the Data Base

1. Importance of a Hardcopy Version

Because the experiments were categorized by research area, this technical memorandum (1) identifies for current and would-be investigators the major areas of research that have been of interest to previous investigators, (2) documents the chronological history/progression of the low-gravity research in each of these major areas, (3) permits identification of areas of research that have been ignored or insufficiently examined, and (4) illustrates the success of any one area of research as it relates to (a) understanding low-gravity fluid sciences or (b) exploiting the low-gravity environment for advanced technology.

Although experimental efforts can be arranged chronologically and by specific areas of research using an electronic form of the data base, the electronic compilation does not easily illustrate many aspects of the progression of low-gravity research. Thus, the hard-copy version is both a teaching tool to users previously unfamiliar to low-gravity experimentation and a chronological history of low-gravity research. The chronological history is of special value because it enables the user to (1) determine if the low-gravity experimental program has progressed in a logical manner, (2) determine which low-g governing fluid parameters are now sufficiently understood and which are still greatly misunderstood, (3) identify areas of research that have been ignored or insufficiently examined, (4) examine the success of any one area of research as it relates to (a) understanding low-gravity fluid sciences or (b) developing advanced technologies and (5) evaluating the low-gravity program as a whole in terms of cost versus return.

2. The Chapters (Categories) of This Technical Memorandum

There are 18 chapters (or major categories) in this TM (see table 5).

Table 5
Chapters in this TM

Chapter 1:	Bioprocessing/Biological Experiments
Chapter 2:	Capillarity
Chapter 3:	Combustion
Chapter 4:	Composites with Gases
Chapter 5:	Composites with Solid Particles
Chapter 6:	Critical Point Phenomena
Chapter 7:	Containerless Processing
Chapter 8:	Crystal Growth from Solution
Chapter 9:	Crystal Growth from the Melt
Chapter 10:	Crystal Growth from the Vapor
Chapter 11:	Diffusion
Chapter 12:	Fluid Physics
Chapter 13:	Liquid Phase Sintering
Chapter 14:	Metals and Alloys
Chapter 15:	Physical Chemistry/Phase Transition
Chapter 16:	Protein Crystal Growth
Chapter 17:	Systems Exhibiting a Miscibility Gap
Chapter 18:	Technological Experiments

All of the chapters were arranged to illustrate the chronological progression of research in each discipline, while grouping together all the experiments a single principal investigator initiated within that discipline. The experiment series of an investigator are listed together so that the progress and consistency of a particular body of work can be examined. For example, in Chapter 15 (Physical Chemistry/Phase Transition), the first four investigators to perform research in this area were (1) G. H. Otto, (Ice Melting in 1973), (2) J. Ehrhardt (Dispersion Electrolysis in 1977), (3) C. J. Raub (Cathodic Hydrogen Formation in 1977), and (4) G. Mix (Electrochemical Corrosion in 1978). However, J. Ehrhardt had four dispersion electrolysis experiments that were all related to each other (the initial 1977 experiment and then experiments in 1981, 1983, and 1984), and C. J. Raub had two Cathodic Hydrogen Formation Experiments (1977 and 1982). Thus, rather than listing the experiments purely chronologically, dispersing, for example, Ehrhardt's like experiments throughout the chapter, his are grouped together under his first experiment. Thus, the logical progression of Ehrhardt's research in this discipline can be examined as well. The chapter sequence, then is as follows:

Physical Chemistry/Phase Transition

(Listed Primarily Chronologically,
but with Investigative Series of Principal Investigators Intact)

Otto, G. H., et al.: Ice Melting (Skylab, 1973)

Ehrhardt, J., et al.: Dispersion Electrolysis (TEXUS 1, 1977)

Ehrhardt, J.: Dispersion Electrolysis (TEXUS 4, 1981)

Ehrhardt, J., et al.: Dispersion Electrolysis (TEXUS 7, 1983)

Ehrhardt, J.: Dispersion Electrolysis (TEXUS 9, 1984)

Raub, C. J., et al.: Cathodic Hydrogen Formation (TEXUS 1, 1977)

Raub, C. J.: Cathodic Hydrogen Formation/Bubble Electrolysis
(TEXUS 6, 1982)

Mix, G.: Electrochemical Corrosion (TEXUS 2, 1978)

Even though the data base compilation is broken down into 18 different major research areas (chapters), each chapter contains several different scientific disciplines. Although the titles of some chapters adequately describe the types of experiments contained within that chapter, the titles of four of the chapters are so broad that a more detailed explanation of the many different scientific disciplines contained therein is required.

Chapter 1: Bioprocessing/Biological Experiments

Many different experiments have been performed on low-gravity vehicles that were related to biological or life sciences. However, several were not related to, directly dependent on, or affected by, low-gravity fluid flow. For example, while experiments were performed to observe animal and human reactions to space (e.g., determine if bumble bees can fly in low gravity, study human vestibular system functioning, etc.), these experiments were inappropriate for a data base that was created to analyze and understand fluid response to low-gravity accelerations. Although both the bee and vestibular experiments may have some fluid dynamics dependence, the objectives of the investigators did not center on understanding low-gravity fluid flow.

Initially, it was decided that bioprocessing and biological experiments should not be contained within the data base. Instead, the base would be limited to fluids and materials processing initiatives. However, after reviewing many of the low-gravity bioprocessing and biological experiments, it was clear that

several (1) were highly dependent on fluid dynamic response, and (2) had fluid systems similar to those of many materials processing initiatives. For example, during an electrophoresis demonstration, charged particles in solution (biological cells) can be separated according to their net surface charge in the presence of an electric field. On Earth, (1) heat produced by the electric field can initiate and sustain thermal convection in the fluid system and (2) cells of highest density settle to the bottom of the system before separation can occur. In the low-gravity environment, such thermal convection and particle sedimentary effects should be reduced, allowing improved separation of important biological cells. Thus, like many fluids and materials processing experiments (such as those pertaining to systems with miscibility gaps or those involving the solidification of composites with solid particles), electrophoresis experiments seek to determine to what degree convective flow and particle/bubble sedimentation are reduced.

Determining which biological experiments should be included in the data base was significantly difficult to determine. Experiment selection criteria was based on (1) if low-gravity fluid dynamics response was detailed in the post-flight analysis and/or (2) if the biological experiment employed a fluid mechanism similarly observed in nonbiological experiments within the data base (such as liquid-liquid diffusion, solutally driven convection, etc.).

Experiments within the Bioprocessing/Biological Experiments chapter center around the following disciplines:

1. Attachment of Human Kidney Cells to Microcarrier Beads
2. Blood Storage
3. Cell Secretion (Microtubule Assembly)
4. Collagen Polymerization
5. Electrofusion of Protoplasts
6. Electrophoretic Separation
7. Fibrin Structure Formation/Fibrin Clot Formation
8. Isoelectric Focusing
9. Lymphocyte Proliferation
10. Phase Partitioning
11. Suspension of Submicroscopic Particles (Colloidal Systems)
12. Thin Film Membrane Formation (Formation of Macromolecular Aggregates During a Film Forming Process).

It should be noted that experiments involving protein crystal growth can be found in Chapter 16.

Chapter 2: Capillarity

Many experimental systems are governed by capillary forces, including fluid systems with a free surface, dispersed bubbles, etc. However, not all such experimental systems are incorporated in this chapter. More specifically, the Capillarity chapter contains experiments that did not experience thermally-driven capillary flow. For example, experiments involving the formation and stability of liquid bridges (columns of liquid suspended between two coaxial discs) are included in Chapter 2 while experiments related to the melting and solidification (and resultant surface-tension driven flow) of a free-surface floating zone are not included. Foaming experiments and bubble interaction experiments that did not involve melting and solidification are also included. (Foaming experiments related to metallic melting and solidification can be found in Chapter 4: Composites With Gases).

Experiments within the Capillarity chapter center around the following topics:

1. Capillary Rise and Associated Wetting Kinetics
2. Chemical Reaction Foaming
3. Capillary Wicking
4. Growth and Coalescence of Gas Bubbles Within an Aqueous Solution and Formation of these Bubbles Into a Polyhedral Foam.
5. Liquid Bridge Formation
6. Liquid Bridge Stability
7. Capillary Properties of Liquid Bridges
8. Capillary Waves on Water Surfaces
9. Formation and Properties of Thin Films Formed Between A Contacting Solid and Liquid
10. Freezing of a Water Liquid Bridge
11. Role of Wetting in Fluid Transfer.

Chapter 12: Fluid Physics

Considering that the major goal of the data base was to identify and describe experimental payloads illustrating a dependency on reduced-gravity fluid phenomena, nearly all of the experiments could have been placed in this single chapter. Instead, the chapter contains experiments that had the following major objective: to evaluate and analyze the fluid physics governing the selected experimental system (not study solidification, liquid bridge assembly, protein crystal growth, biotechnology, etc.).

Experiments within the Fluid Physics chapter center around the following topics:

1. Acceleration Disturbances to a Liquid-Vapor Interface
2. Characterization of Rocket Vibration Environment by Measurement of the Mixing of Two Liquids
3. Liquid Transfer/Spreading
4. Liquid Lens Formation
5. Liquid Film Formation
6. Liquid Sloshing (experimental payloads only)
7. Liquid Motion in Partially Filled (Spinning) Containers
8. Experiments Designed to Specifically Examine Heat Flow and Convection (including Thermocapillary and Interfacial Convection)
9. Bubble and Water-Drop Physics (including Acoustic Positioning of Bubbles and Water Drops)
10. Bubble Transport by Chemical Waves
11. Separation of Fluid Phases
12. Thermocapillary Drop/Bubble Motion
13. Powder Flow
14. Cloud Formation
15. Contact and Coalescence of Viscous Bodies
16. Solid/Liquid Collisions
17. Glass Fining
18. Super Fluid Helium Examinations

Chapter 18: Technological Experiments

A great number of fluids and materials experiments performed in the reduced-gravity environment were initiated to:

- (1) Demonstrate that activities or procedures habitually performed on Earth (and dependent on fluid flow) could be successfully performed in the reduced-gravity environment (i.e., brazing, soldering, electroplating, tribology, mass measurement)
- (2) Evaluate operation of fluid-physics-dependent equipment (i.e., halogen lamps, acoustic positioning hardware, liquid lasers)
- (3) Demonstrate new or improved technology (i.e., skin technology, skin casting, production of monodisperse latex particles, superior paper production, space art, heat pipe development), or
- (4) Evaluate the space environment (i.e., acceleration measurements, space vacuum).

These experiments were placed in the Technological Experiments chapter.

Experiments within the Technological Experiments chapter center around the following topics:

1. Brazing
2. Soldering
3. Electroplating
4. Skin Technology
5. Slip Casting
6. Tribology
7. Mass Measurement
8. Acoustic Positioning Hardware Evaluation
9. Halogen Lamp and Metal-Halide Arc Lamp Performance
10. Heat Pipes/Thermal Control of Experiments
11. Production of Monodisperse Latex Particles
12. Acceleration Measurement
13. Actual In-Orbit Refueling (see also the Fluid Physics Chapter for related studies)
14. Art
15. Sampling of the Space Vacuum
16. Operation of Liquid Laser
17. Performance of Computer Chips
18. High Performance Liquid Chromatography
19. Paper Formation.

3. Available Indices

This hard-copy version of the data base is accompanied by seven Indices (A to G) that allow readers to locate topics of interest:

- | | |
|----------|---|
| Index A: | Key Words |
| Index B: | Investigators (Principal and Co-Investigators) |
| Index C: | Payload Type |
| Index D: | Processing Facility (Including Facility Acronyms) |
| Index E: | Sample Materials |
| Index F: | Container Materials |
| Index G: | Mission |

Index A lists (alphabetically) all the words contained within the 600 key words data fields. Key words include (1) the major research area (or category/chapter) of the experiment and (2) a multitude of additional words that describe the experiment (including boundary conditions, governing fluid phenomena, desirable and undesirable fluid characteristics, etc.).

Significant care was taken to select a specific key word string to represent subjects of interest in the data base (and then repeat this specific string throughout all the applicable records). For example the key word string "Fluid Oscillation" was selected and repeated in all applicable records rather than using an array of other similar key words strings throughout individual records (i.e., Oscillating Fluids, Liquid Oscillation, Oscillating Liquids, etc.).

It is important to note that the page numbers listed in Indices A, E , and F do not indicate the actual page on which the key words, sample materials, and crucible materials are located, but instead detail the page on which the experiment summary begins. (Page numbers listed in indices B, C, D, and G do indicate actual page numbers on which information concerning investigators, payload types, processing facilities, and missions appear.)

4. Special Nomenclature/Features in the Data Base

A. Shuttle Mission Nomenclature

Shuttle mission numbers have changed significantly throughout the STS program, and many of the earlier shuttle flights have had multiple designations. For example, for the first 25 shuttle flights (using the nomenclature described in Reference 100), the shuttle had a (sequential) launch number, at least one STS number, and a mission code.¹⁰⁰

Prior to the actual shuttle flights, missions were assigned an STS number, indicating in what sequence they were manifested. In Reference 100, these were denoted as STS-0__ numbers. However, early in the shuttle program, the flights were more commonly identified using the letters "STS" followed by the launch number (e.g., STS-1, STS-2).

The most common mission designations for the first four flights (1981-1983) were the STS numbers that were represented as STS-1 through STS-4. Because the first four missions were considered orbiter flight tests (OFT's), the mission codes for these missions were OFT-1 through OFT-4.

Mission designations for the first four shuttle flights
(most common designation underlined)

Launch No.	STS Number(s) STS-Launch No./Manifest No.	Mission Code
1	<u>STS-1</u> /STS-001	OFT-1
2	<u>STS-2</u> /STS-002	OFT-2
3	<u>STS-3</u> /STS-003	OFT-3
4	<u>STS-4</u> /STS-004	OFT-4

Beginning with the 10th shuttle mission, the assigned shuttle manifest numbers (STS-0_ _) no longer paralleled STS launch numbers. This miss-match resulted because the 10th manifested shuttle mission (STS-010) was canceled. Thus, STS launch No. 10 was actually the flight of the 11th manifested flight (STS-011).¹⁰¹ Once these manifest numbers were out of sequence with the launch numbers and later, as more manifested STS flights were canceled, the STS manifest numbers deviated further and further from the launch numbers. To add to the confusion, the now more popular mission codes (then represented by a two-digit number followed by a letter, (i.e., STS 41-B)) eventually did not proceed sequentially either.

Although the most common mission designations for flights 5 through 9 were STS-5 through STS-9, the most common designations for flights 10 through 25 were the two-digit/number mission codes.

Mission designations (most common designation underlined)

Launch No.	STS Number(s) STS-Launch No./Manifest No.	Mission Code
5	<u>STS-5</u> /STS-005	31-A
6	<u>STS-6</u> /STS-006	31-B
7	<u>STS-7</u> /STS-007	31-C
8	<u>STS-8</u> /STS-008	31-D
9	<u>STS-9</u> /STS-009	41-A
10	STS-011	<u>41-B</u>
11	STS-013	<u>41-C</u>
12	STS-014	<u>41-D</u>
13	STS-017	<u>41-G</u>
14	STS-019	<u>51-A</u>
15	STS-020	<u>51-C</u>
16	STS-023	<u>51-D</u>
17	STS-024	<u>51-B</u>
18	STS-025	<u>51-G</u>
19	STS-026	<u>51-F</u>
20	STS-027	<u>51-I</u>
21	STS-028	<u>51-J</u>
22	STS-030	<u>61-A</u>
23	STS-031	<u>61-B</u>
24	STS-032	<u>61-C</u>
25	STS-033	<u>51-L</u>

In 1988, (beginning with the 26th launch) STS mission codes were no longer employed. Instead, STS designations were referenced by either the launch number or the STS letters followed by a two-digit manifest number. Once again, the nomenclature was confusing as the STS launch numbers eventually did not parallel shuttle manifest numbers.

A typical Mission field for an STS experiment in the data base flown in 1988 or later is:

Mission: STS Launch #30, STS-32 (Columbia)

B. Sample Materials/Container Materials Nomenclature

Often times, investigators express sample and container materials in terms of chemical formulas. For example, aluminum-indium alloys are expressed as "Al-In alloys". Similar nomenclature was desired for the data base sample-materials-field and container-materials-field. However, if a data base user was interested in locating all experiments that employed indium (In) and searched an electronic form of the data base for this short string of letters (say "..In.."), records that had the following words in the sample materials section would also be singled out: inert gas, influenza virus, ink, interferon, etc.

Thus, in an effort to insure data base users could search effectively for materials employed, a special nomenclature for these chemical formulas was adopted. Instead of writing only the string AlIn, in the materials field, Al*In* was written (each element symbol being followed by a star (*)). Using this nomenclature, a user searches for the string "In*" to locate experiments employing indium.

When searching for a material of interest (either using an index in this hardcopy version or on a sophisticated (searchable) electronic version of the data base), it would be wise to search for the following character strings: (1) "Al*In*", (2) "In*Al*", (3) "Al*", (4) "In*", (5) "aluminum", and (6) "indium".

In addition, because most data base software packages cannot handle upper and lower case numbers, chemical equations were difficult to reproduce for searching capabilities. Thus, a simplified representation of these equations was adopted. Examples of complicated element strings in the data base are as follows:

- (1) If a user was interested in looking for all experiments related to AgCu with Al₂O₃ additions, he could search under "Ag*Cu*Al*O*"
- (2) If a user was interested in looking for all experiments employing ammonium chloride (NH₄Cl, he could search under either
 (1) "ammonium chloride" or (2) "N*H*Cl*"

(3) If a user was looking for all experiments employing cadmium telluride doped with chlorine, he could search under

(1) "cadmium telluride", (2) "chlorine" or (3) "Cd*Te*Cl*".

Sample and crucible materials were often represented in multiple ways (in their respective data fields) to insure data base users could find materials of interest.

C. Quotes in Experiment-Descriptive Summaries

As detailed on p. 58, information that was difficult to understand was often quoted directly from the source and placed into the experiment summaries. Quotes were also used to highlight major experimental results, report critical information related to the experiment, identify experiment anomalies, or to simply restate information as provided in available sources. Quotes (in the data base) are usually followed by a reference number (applicable references are listed at the end of each experiment record) and a page number, i.e., "(1, p. 32)" (which indicates the quote was attained from Reference (1), page 32).

An example of the use of quotes in an experiment summary can be seen in this excerpt from an investigation by H. Wishnow et al. on STS 61-C (quotes highlighted for illustrative purposes only):

Principal Investigator(s): Wishnow, H. (1), Kurtz, E. (2)
Mission: STS Launch #24, STS-032 (STS 61-C, Challenger)
Launch Date/Expt. Date: January 1986

Experiment:

Reaction of Oil Paints on Canvas to Space Travel

The specific objective of this STS-032 experiment was to determine the effects of vibration, temperature change, reduced gravity, and excessive g-stresses on fine arts materials.

Primed and unprimed linen samples, some of which were painted with oil colors using a wide variety of pigments, were employed as test materials. On Earth, the paints were applied using traditional artistic methods, creating actual paintings similar to those which may some day be transported or created on space flights.

The samples were rolled between layers of polyurethane foam and placed in the G-481 Get Away Special (GAS) canister. A thermograph was inserted into the center of the roll to record temperature changes within the can at hourly intervals.

After the 6-day mission, the samples were evaluated by several techniques including X-ray and ultraviolet examination. The following results were reported (2, p. 115):

- "A. The linen and painted surfaces showed no sign of oxidation.*
- B. The surfaces showed no accumulation of foreign substances.
- C. The surface layers were fully intact with no evidence of cracking* or flaking* of the pigments.
- D. There was no sign of cupping or cleavage.*"

Reportedly, "Temperature changes within the G. A. S. canister were not recorded due to an error in the programming of the thermograph." (2, p. 115)

The investigators concluded that no degradation was apparent and that "...materials of the fine arts can be transported for limited periods of time into space and returned safely." (2, p. 115)

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References/Applicable Publications:

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(2) Kurtz, E. and Wishnow, H.: The Transportation of Fine Arts Materials Aboard the Space Shuttle Columbia. In the 1988 Get Away Special Experimenters' Symposium, Cocoa Beach Florida, September 27-29, 1988, NASA CP-3008, pp. 113-119. (post-flight)

D. Notes in Experiment-Descriptive Summaries

As stated on p. 58, notes from the author of the experiment summary (designated in the experiment-descriptive text as "<Note:...>") are included to (1) detail a variety of difficulties encountered in preparing the experiment summary or (2) communicate other useful information to the reader not necessarily directly related to the experiment itself. Notes were most often written to indicate that available information was either (1) conflicting with other sources, (2) difficult to understand, (3) did not follow a logical path, (4) not published in English, and/or (5) not received prior to the release of the TM.

An example of the use of two such notes in an experiment summary can be seen in this excerpt from an investigation by S. Aalto during the MASER 1 mission (<Notes:> are highlighted on the next page for illustrative purposes only):

Principal Investigator(s): Aalto, S. (1)

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Mission: MASER 1

Launch Date/Expt. Date: March 1987

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Experiment:

Thermal Conductivity of Electrically Non-conducting Liquids

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This MASER 1 experiment was designed to measure the thermal conductivity of an electrically non-conducting liquid using a transient hot wire technique.

Two fluid cells within the MASER Fluid Science Module (FSM) were dedicated to the experiment. **<Note: It is unclear if these cells were cylindrical, three-dimensional rectangular, or two-dimensional rectangular, although they appear to have been cylindrical.>** Prior to the flight, each cell was filled with pure ethanol and configured with a 50-micron diameter platinum (hot) wire. The wire stretched down the center, vertical (long) axis of the cell.

<Note: Although it was reported that one cell was "preheated" to 30 °C and the other to 50 °C, it is unclear if this heating was initiated prior to the start of the low-gravity phase or after the low-gravity phase had been obtained. (It appears that the liquid in each cell was warmed by an outer, concentric cylindrical heater (the same length as the cell)).>

During the experiment, a constant current was passed through the wires. Thermal conductivity measurements were derived from voltage drops which occurred across the 100-mm measuring length of the wire. The temperature in the liquid was measured by two thermocouples located near the wire.

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E. Brief Notes Following References

Many references detailed in each of the experiment records have brief notes following them to (1) alert the reader that the document was published in a foreign language, (2) indicate that the text discusses either preflight or post-flight issues, (3) identify what mission results are discussed therein, or (4) indicate that something other than results or preflight information is discussed (e.g., processing facility design, related acceleration measurements, etc.). Examples of such reference notes can be seen in the following excerpt from E. G. Lierke's TEXUS 14b experiment (with notes highlighted and underlined for illustrative purposes only):

Principal Investigator(s): Lierke, E. G. (1)
Mission: TEXUS 14b
Launch Date/Expt. Date: May 1987

Experiment:
Acoustic Positioning

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.(Experiment Summary Omitted Here)

References/Applicable Publications:

(1) Lierke, E. G., Grossbach, R., Fogel, K., and Clancy, P.: Acoustic Positioning for Space Processing of Materials Science Samples in Mirror Furnaces. Symposium in Industrial Activity in Space, Stressa, Italy, May 2-4, 1984, Proceedings, Paris, Eurospace, 1984, pp. 116-126. (preflight; TEXUS 1 results)

(2) Lierke, E. G. and Grossbach, R.: Akustische Positionierung. In BMFT/DFVLR TEXUS 13-16 Abschlussbericht 1988, pp. 90-93. (in German; post-flight)

(3) Experimentmodul TEM 02-2. In BMFT TEXUS 13-16 Abschlussbericht 1988, pp. 90-93. (in German; post-flight)

(4) Lierke, E. G., Grossbach, R., Flögel, and Clancy, P.: Acoustic Positioning for Space Processing of Materials Science Samples in Mirror Furnace. In Proceedings of the 1983 Ultrasonic Symposium, October 31 - November 1-3, 1983, pp. 1129-1139. (preflight; theoretical discussion; TEXUS 1 results; TEXUS 9 proposal)

(5) Clancy, P. F., Lierke, E. G., Grossbach, R., and Heide, W. M.: Electrostatic and Acoustic Instrumentation for Material Science Processing in Space. Acta Astronautica, Vol. 7, 1980, pp. 877-891. (preflight; discusses experiment apparatus)

5. Naming the Data Base

When the compilation was first created, it was called the Fluids And Materials Experiments (FAME) data base. At the request of NASA headquarters, the name was changed to indicate that the base documented reduced-gravity experiments. Thus, the compilation is currently known as the Microgravity Research Experiments (MICREX) data base.

VIII. Electronic Manipulation and Access of the Data Base

1. In-House Manipulation of Data (PC Software)

Initially, all of the data pertaining to fluids and materials processing experiments was stored in a personal computer using an off-the shelf (commercial) data base software package called REFLEX (by Borland Co.). Originally, this software was an acceptable choice for electronically manipulating the in-house version of the MSFC data base. However, when it was determined that (1) extensive electronic writing/editing of experiment summaries was necessary and (2) hardcopy (publication-quality) retrieval of experimental records was desired, REFLEX could not be easily employed to obtain these tasks. Instead, the REFLEX data files were transferred into files that could be edited and printed with a word processor. Eventually, the contents of the word processor files were transferred into another PC commercial data base software package called 4th Dimension (by ACIUS, Inc.). The current MSFC (in-house) working version of the data base is still manipulated via this software.

2. World-Wide Web Electronic Access to MICREX

An electronic version of the MICREX data base is available online and can be accessed via the World Wide Web (WWW) using various Hypertext Markup Language browsers such as AIR Mosaic, NCSA Mosaic, Mosaic Netscape, or Cello (fig. 26). MICREX can be directly accessed with the following address:

<http://otis.msfc.nasa.gov/fame/Fame.html>

This WWW version, which currently contains information on over 800 fluids and materials processing experiments (the 600 contained in this TM and over 200 more-recent experiments), is updated periodically from the MSFC PC working version of MICREX. These periodic updates are performed to place information pertaining to new experiments into the compilation or to expand information on experiments already within the data base.

Currently, the WWW version of the data base contains information on experiments performed during the following programs:

- (1) U.S. Mercury, Apollo, Skylab, and Apollo-Soyuz (1962-1975)
- (2) U.S. Space Processing Applications Rocket (SPAR) sounding rocket (1975-1983)
- (3) U.S. Space Shuttle (1982-1994)
- (4) U.S. Consort sounding rocket (1989-1992)

- (5) German Technologische Experimente unter Schwerelosigkeit (TEXUS) sounding rocket (1977-1991)
 (6) Japanese TT-500A sounding rocket (1980-1983)
 (7) Swedish Materials Science Experiment Rocket (MASER) (1987-1988).

A breakdown of the number of experiments performed during each program (as of April 1995) is presented in table 6.

Table 6
 Number of Experiments (by Mission)
 Contained in the WWW Version of Micrex

Mercury and Apollo	11
Skylab	46
Apollo-Soyuz Test Project	10
U.S. Space Shuttle	422
Spacelab Missions	
Spacelab 1 (1983)	36
Spacelab 2 (1985)	3
Spacelab 3 (1985)	5
Spacelab D1 (1985)	49
Spacelab D2 (1993)	41
Spacelab J (1992)	40
USML-1 (1992)	37
IML-1 (1992)	23
IML-2 (1994)	18
SLS-1 (1991)	13
Middeck	62
Payload Bay *	95
SPAR	46
TEXUS	209
TT-500A	14
MASER	15
Consort	56
	829

* Excluding Spacelab Missions, but including (1) GAS Cans and MAUS cans, (2) Payload Bay Carrier Systems (e.g., MEA, MSL, USMP), (3) Free Flying Satellites deployed from the Payload Bay (e.g., LDEF and SPAS).

3. Searching Capabilities/Limitations of the MICREX Data Base on the WWW

The WWW electronic version of MICREX has some limited searching capabilities. Users can obtain listings (called indexes) of experiments by subject, mission/payload-type, or principal investigator. After an index type is selected and listed, users scroll down the listing and select (click on) an experiment record of interest. Experiment summaries (similar to the ones in this TM) are then displayed for review.

The subject index allows users to see the data much like it is arranged in this TM. Experiments are grouped together (chronologically) by subject (i.e., categories). These subjects are essentially the same as the chapters listed in this TM:

- Biotechnology
- Capillarity
- Combustion
- Composites with Gases
- Composites with Solid Particles
- Critical Point Phenomena
- Containerless Processing
- Crystal Growth from Solution
- Crystal Growth from the Melt
- Crystal Growth from the Vapor
- Diffusion
- Fluid Physics
- Liquid Phase Sintering
- Metals and Alloys
- Physical Chemistry/Phase Transition
- Protein Crystal Growth
- Systems Exhibiting a Miscibility Gap
- Technological Experiments
- Miscellaneous Experiments

The mission/payload-type index allows users to list experiments of a certain payload type (such as all Gas Can Experiments). The listings are chronological by mission. The following payload types can be selected and listed:

- Long Duration Exposure Facility (LDEF)
- Mercury
- Skylab
- Sounding Rocket
- Get Away Special (GAS)
- Middeck
- Payload Bay
- Spacelab
- High School and College Experiments

The principal investigator index groups experiments alphabetically by the first principal investigator listed in the experiment record. For example, if the principal investigators of an experiment were both Grodzka and Facemire, (and Grodzka was listed first in the data record) the experiment information would be found alphabetically in the listing under "G". Unfortunately, this same experiment record is also not listed alphabetically under "F" for Facemire, nor can the user search for all of the experiments Facemire has been involved in as a principal or co-investigator. Likewise, the user can not search for all the experiments performed by any particular principal or co-investigator; he can only see a summary of experiments arranged alphabetically by the first investigator listed in the record.

Other searching options of the WWW version of MICREX are not yet available. For example, although each experiment record has a detailed key words section (which was very carefully prepared to guide users to experiments of interest by (1) category (subject), (2) governing fluid phenomena, (3) desirable and undesirable fluid characteristics, etc.), this field cannot currently be searched on the electronic version. If such a searching capability becomes available, the indices contained in this hardcopy TM could be employed to enable users to search quickly for subjects of interest. This hardcopy version (with indices) does give readers the option of searching for items of interest.

For most purposes, effective searching through the 800 fluids and materials processing experiments currently residing on the electronic version of the data base would require sophisticated computational assistance. In the ideal situation, users could group experiments together based on either one or a multitude of criteria including: (1) selected key words, (2) similar materials processed, (3) experimental methods employed, (4) principal investigators involved, etc. As stated above, this capability does not currently exist on the WWW MICREX version.

4. Possible Additional Networking of the Data/Possible Enhanced Search Capabilities

It is expected that the electronic version of MICREX will also be made available on either the NASA Research Connection (ReCon) scientific information system or the NASA Aerospace Research Information Network (ARIN). Because both of these systems have sophisticated searching capabilities (almost any data field can be effectively searched), manipulation of the MICREX information would be greatly enhanced. Placement of MICREX on ReCon or ARIN would insure that the data base is readily available to all NASA employees as well as a multitude of scientific communities that already employ these systems.

5. Draft of Data Base on MSAMS

Presently, an old draft of the data base (containing information on the initial 600 experiments placed in MICREX), is also available on-line through NASA Langely's Microgravity Science Applications System (MSAMS). Access to the data base using MSAMS is free of charge and readily available using either INTERNET or a modem. To obtain a password and access instructions, call Vivian Lewis, CTA, Incorporated, (804) 827-6701.

6. MICREX Data Availability Via ESA's MGDB

Presently, some of the MICREX data resides in the European Space Agency's (ESA's) MicroGravity DataBase (MGDB). A prototype of the fully searchable MGDB is now available over the WWW. The address is:

<http://www.esrin.esa.it/htdocs/mgdb/mgdbhome.html>

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X. Appendix



Center for Space and Advanced Technology
Technical Center

4/15/88

Dear Dr.

A compilation of information concerning all known fluids and materials processing experiments performed in the space environment is being assembled by the Fluid Dynamics Branch of the Marshall Space Flight Center (NASA). The Center for Space and Advanced Technology (CSAT) is assisting NASA in this compilation. The first version of the data base will profile experiments giving name, location and affiliation, experiment title, applicable publications etc and also provide a brief experiment description. Currently the data base identifies approximately 600 separate experiments which have flown on Apollo, Skylab, SPAR, TEXUS, MASER, Salyut/Soyuz and Space Shuttle missions. NASA plans to publish this compilation this year as a resource for use by the scientific community. Since most of this information has been obtained from the open literature where there are different styles and purposes for publication, fitting the information into one format has, in some cases, been a challenge.

The Fluid Dynamics Branch of MSFC/NASA and CSAT would like to assure that your research efforts are accurately included in the data base. The attached initial data sheet is offered for your review. Please comment on any discrepancies and provide any additional information, such as additional Co Investigators, etc. If additional publications are available which describe your experimental efforts associated with the space research, please provide references to these articles. Please list all applicable articles, regardless of the language in which they are written. If possible, please send a copy of these publications.

An example of a typical entry into the data base is also attached for your convenience. This example represents information concerning the Geophysical Fluid Flow Cell flown on Spacelab 3 by J. E. Hart. There are two short paragraphs included that aid in the description of the experiment. One is a summary of the experiment. The second concerns application(s) of the materials processed or an explanation of why the space environment is important for such research.

In addition to verifying the information concerning your space experiment, please provide the two short paragraphs described on the previous page for inclusion in the data base. The data base entry form allows up to 18 typewritten lines for the summary and 6 typewritten lines for the applications paragraph. Because of the many requests for this type of information from the scientific community, including current and future investigators, we plan to publish the data base as soon as appropriate, and we certainly desire that your experiment be listed accurately. All responses must be received by May 1, 1988. We believe that this publication will be a valuable reference for academia, industry and government. Thank you for your assistance.

Sincerely

John R. Williams
Vice President

June 15, 1993

Dear Dr.

NASA Marshall Space Flight Center and Wyle Laboratories have compiled a data base containing experiments performed on (1) U. S. Manned space vehicles, (2) payloads deployed from U. S. Manned space vehicles, and (3) all domestic and international sounding rocket programs (excluding those of the U. S. S. R. and China). Approximately 600 of the experiments from the data base will soon be released in hard copy format as a NASA Technical Memorandum (TM) titled "Fluids and Materials Processing Experiments (FAME) Data Base". The complete data base, regularly updated as experiments are flown, is available through NASA Langley's Microgravity Science Applications Management System (MSAMS) Data Base and will be available through the European Space Agency's (ESA's) Micro Gravity Data Base (MGDB). Both MSAMS and MGDB can be accessed through the INTERNET computer network.

To insure that research efforts are accurately represented, your experiment entries, which are to be included in the NASA TM, are enclosed. We ask that you (1) review this information, (2) indicate any discrepancies or inaccuracies within these records, and/or (3) add any additional information where applicable. Please add recently released publications, which directly apply to your experiment, to the REFERENCES/APPLICABLE PUBLICATIONS section. If the EXPERIMENT SUMMARY section needs to be expanded, please add any additional information. We do not plan on adding any additional paragraphs to the EXPERIMENT SUMMARY at this time, unless you provide this information. We have also enclosed a list of data base chapters and have indicated under which chapter your experiments are included. Please indicate if you would like to move your experiments to a different chapter.

All changes and corrections received prior to August 6, 1993 will be incorporated into the NASA TM. Any changes or corrections received after this date will be incorporated into the computerized versions of the data base, but not in this release of the NASA TM. If the experiment records are not returned, we will assume that all information contained in your experiment records is correct and current. This is the second time at least one of the identified Principal Investigators has been contacted in connection with the verification of this data. The previous request for information was either requested by the Center for Space and Advanced Technology (CSAT) or myself.

If you have any questions or comments, please feel free to call me at (205) 544-6904. Thank you for your cooperation.

Sincerely,



Jonathan C. Jones

Typical Summary Sent to Investigators
(Complete with Additional Questions Section)

Principal Investigator(s): Schafer, C. F. (1)

Co-Investigator(s): None

Affiliation(s): (1) National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Alabama

Experiment Origin: USA

Mission: SPAR 1

Launch Date/Expt. Date: December 1975

Launched From: White Sands Missile Range, New Mexico

Payload Type: Sounding Rocket Experiment

Processing Facility: Temperature Control Unit (TCU) furnace (heaters, sample cartridges, water quench system, and sample monitoring thermistors)

Builder of Processing Facility: NASA Marshall Space Flight Center, Huntsville, Alabama

Experiment:

Characterization of Rocket Vibration Environment by Measurement of the Mixing of Two Liquids (74-18)

This SPAR 1 experiment was the first in a series of investigations designed by Schafer et al. to illustrate the nature of the SPAR rocket acceleration environment and its effect on diffusion-controlled fluid systems.

Prior to the SPAR mission, three 0.6 cm cylindrical samples were prepared. Each of these prepared samples consisted of a section of pure indium joined to a similarly-sized section of 80 wt% indium-20 wt% lead. The density differences between the two sections were selected to allow convective mixing to occur if sufficient residual gravity was present when the materials were (later) molten.

Each sample was placed within a separate heater within the experiment Thermal Control Unit (TCU). The three sample/heater assemblies were configured such that each was aligned differently to the rocket longitudinal axis and onboard accelerometer axes when the TCU was mounted in the SPAR rocket.

During the SPAR 1 experiment, the samples were melted and solidified during the low-gravity coasting phase of the mission. Reportedly, the experiment sequence was as follows: (1) 45 seconds after launch, sample heating was initiated, (2) 225 seconds after launch, sample heating was terminated, and (3) 345 seconds after launch, sample quench was initiated.

Typical Summary Sent to Investigators, Cont.

Inspection of the flight data and/or the returned TCU payload indicated that (1) the experiment was performed as scheduled, (2) the samples were processed with the expected thermal profile, and (3) the quench system performed as expected.

Post-flight, the three In-(In-Pb) interfaces were examined to determine the degree of mixing that had occurred in each of the samples. Reportedly, the sample "... (oriented parallel to the payload longitudinal axis) experienced interface motion near that ... expected from diffusion... the sample (aligned parallel to the accelerometer x-axis) experienced a small amount of interface motion... which might be slightly more than that expected by diffusion... and the sample (aligned parallel to the accelerometer y-axis) experienced flow down one side of the container." (1, p. IV-27)

Both experimental and computational correlation of fluid motion with acceleration environment was performed. It was observed that (1) "... the magnitudes of the flow experienced by the three samples... are consistent with the acceleration arising from the rotation of the payload about its longitudinal axis...." (1, p. IV-36), and (2) the level of this acceleration is of the order of 10^{-5} g or less. Thus it was concluded that while the residual accelerations aboard SPAR are very low and the vehicle provides a good platform for experiments requiring up to 5 minutes of low-g time, convective fluid motion can occur at these low-g levels. It was recommended that computations to estimate levels of effective gravity for which convective flows become significant be performed for a given experimental configuration.

Key Words: Fluid Physics, Melt and Solidification, Binary Systems, Alloys, Quench Process, Convection, Density Difference, Liquid Mixing, Liquid/Liquid Interface, Diffusion, Rotation of Payload, Acceleration Effects, Acceleration Measurement

Number of Samples: three

Sample Materials: First section: pure indium; second section: 80 wt% In-20 wt% Pb
(In*Pb*)

Container Materials: aluminum
(Al*)

Typical Summary Sent to Investigators, Cont.

Experiment/Material Applications:

It is expected that the low gravity environment will reduce convective flow in systems with density gradients. This experiment illustrates the need to characterize the acceleration environment and to consider the effects of possible fluid motions even at low acceleration levels.

The In/In-Pb system was chosen for several reasons. First, not only could it be used illustrate the mixing behavior of two fluids of differing density, but it was also expected to yield results which could be interpreted as relevant to other experiments involving differing density fluids. Second, its "...kinematic viscosity is in the range of kinematic viscosities of materials of interest to other investigators (e.g. liquid metals). This follows from the fact that for a fixed geometry, the kinematic viscosity of a fluid is a fundamental parameter for governing flow due to accelerations which act through density differences." (1, p. IV-4) "Thirdly, the materials chosen for sample preparation were selected so as to minimize spurious flow effects." (1, p. IV-4)

References/Applicable Publications:

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Typical Summary Sent to Investigators, Cont.

Contact(s):

Charles F. Schafer

EP55

NASA Marshall Space Flight Center, AL 35812

Typical Summary Sent to Investigators, Cont.

Additional Questions:

Should anyone be listed as a Co-Investigator? If so, please indicate (1) their name, (2) where they worked at the time of the mission, and (3) where they work now.

Additional information has been added to this summary since you received it for review the first time.

XI. Figures

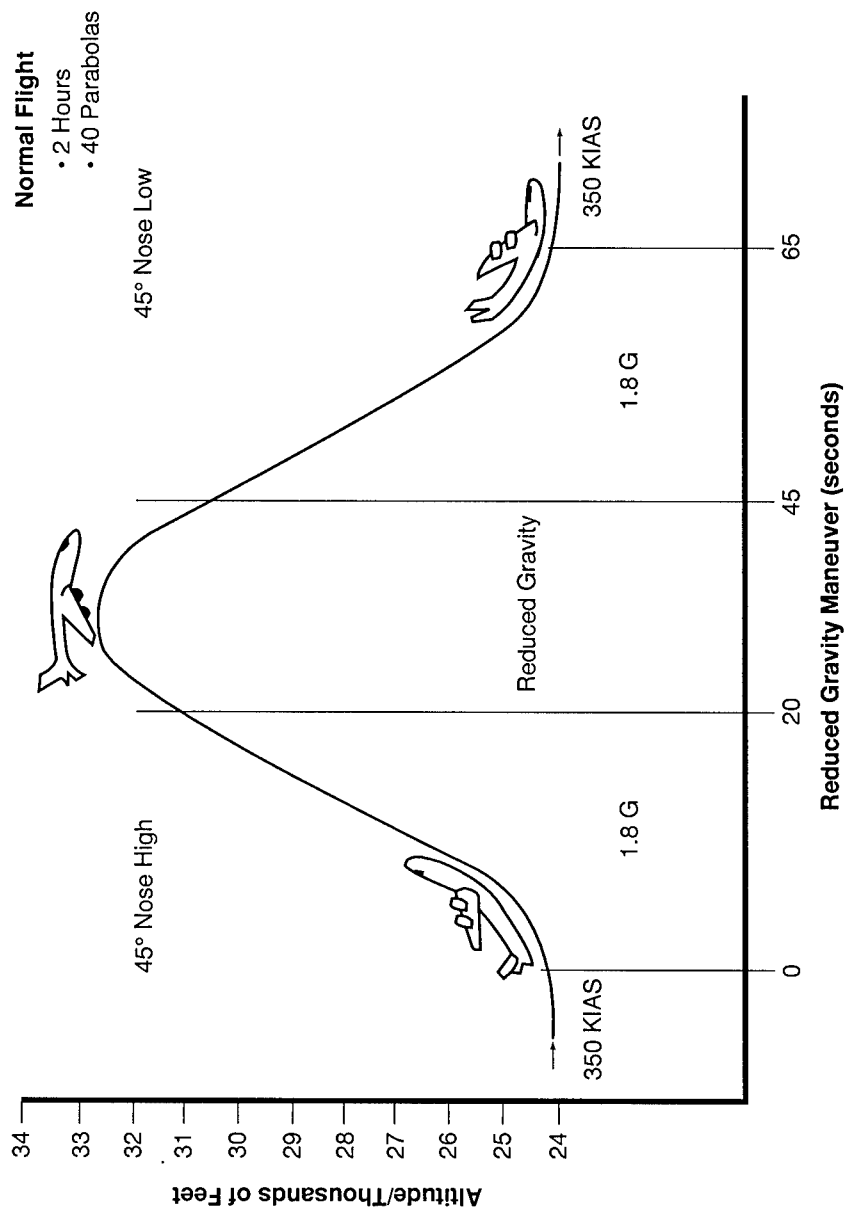


Figure 1. KC-135 aircraft trajectory.¹⁵

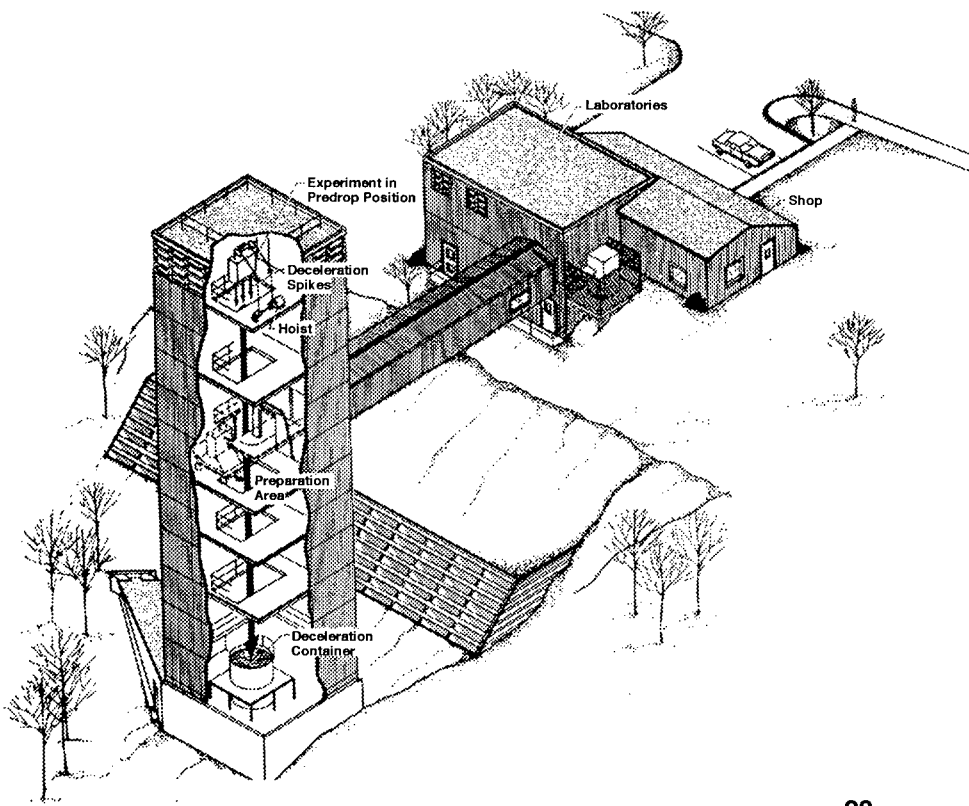


Figure 2. The 2.2-s drop tower at NASA LeRC.²⁰

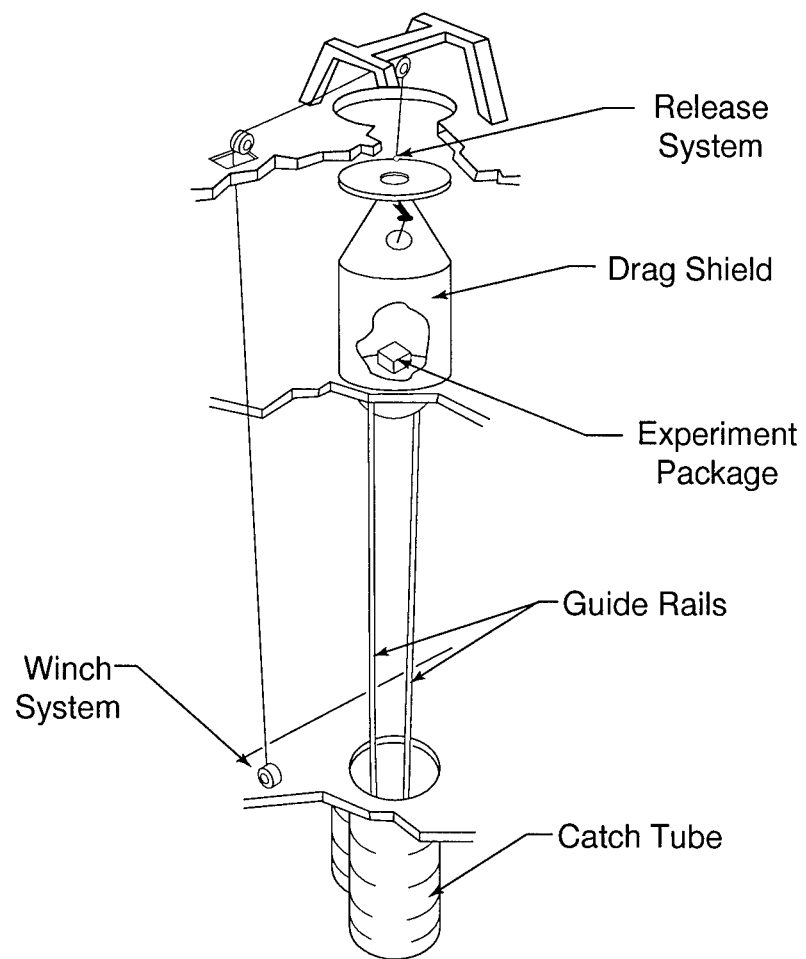


Figure 3. The 100-m drop tower at NASA MSFC.¹⁴

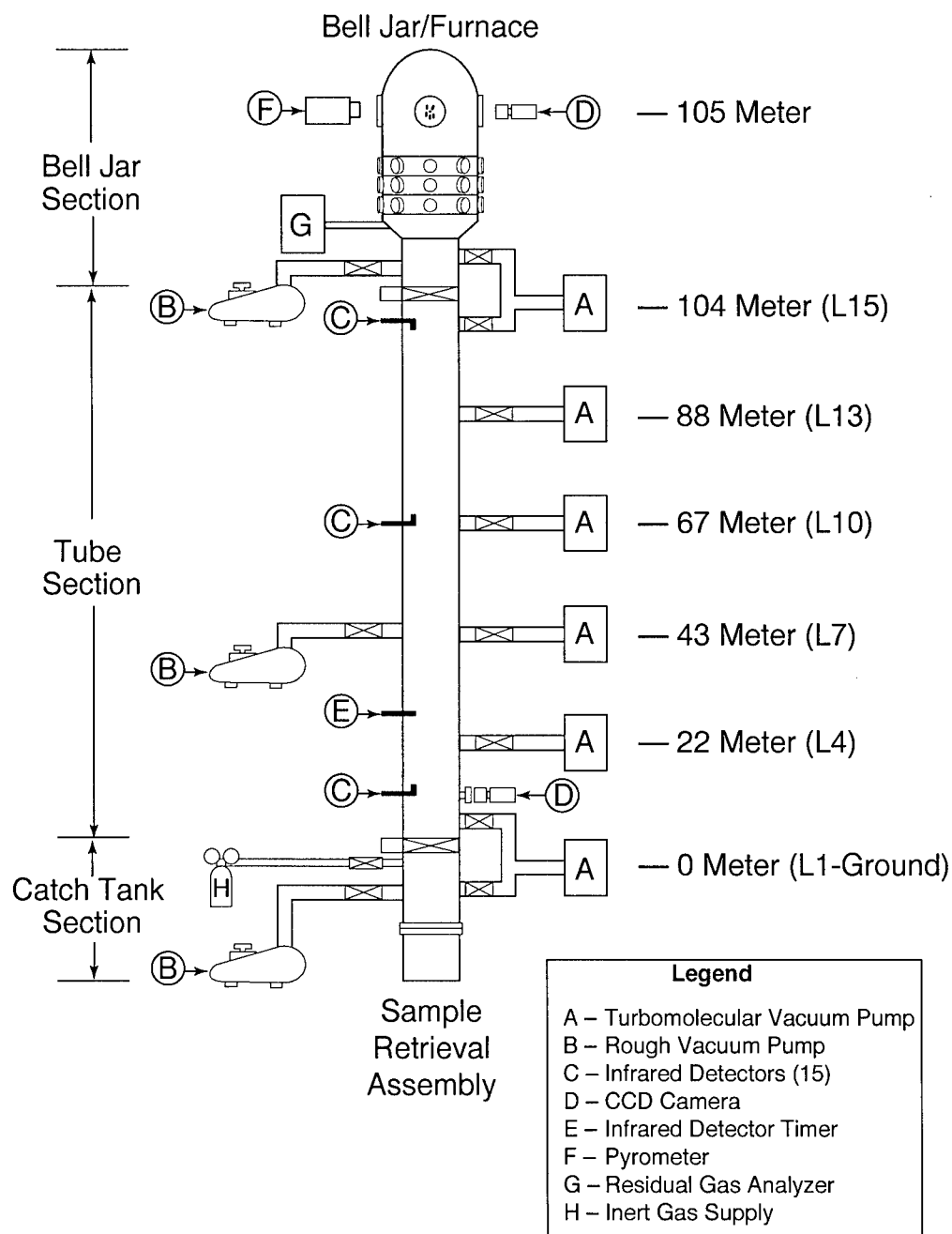


Figure 4. The 105-m drop tube at NASA MSFC.³⁰

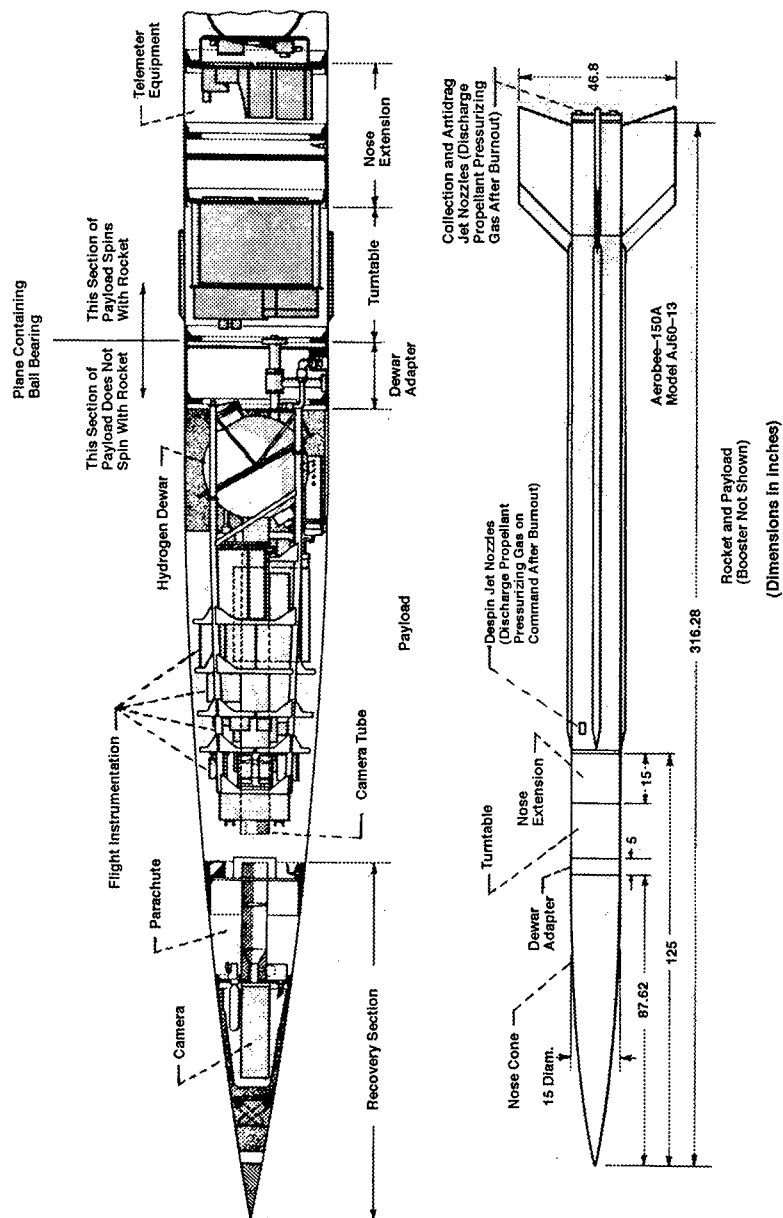


Figure 5. The major components of the Aerobee rocket (flight No. 2).³⁴

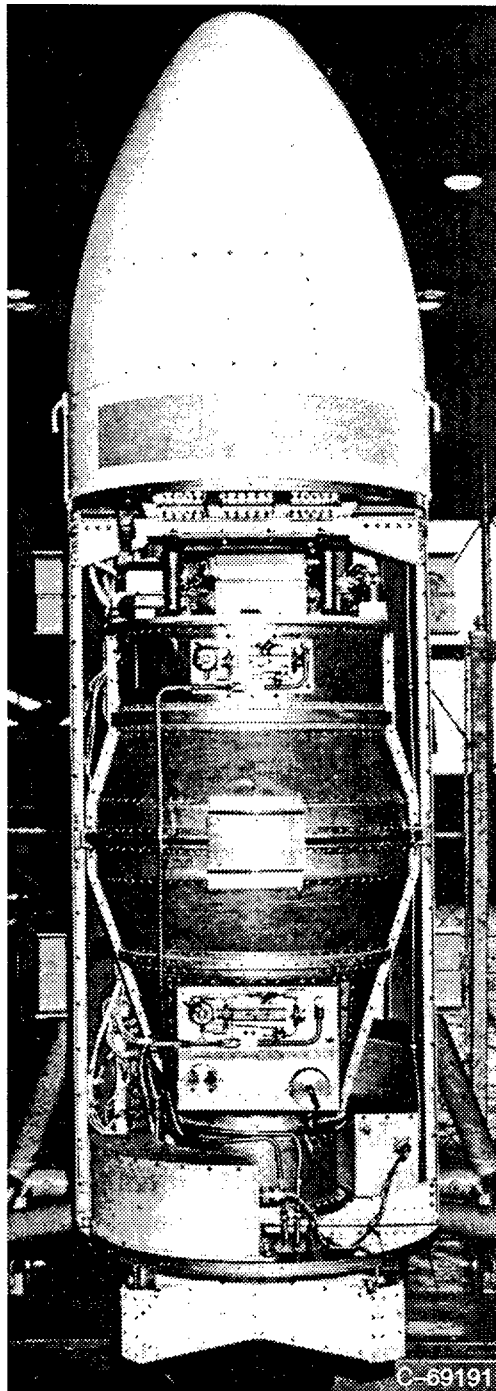


Figure 6. The Atlas flight experiment mounted in the passenger pod.³⁷

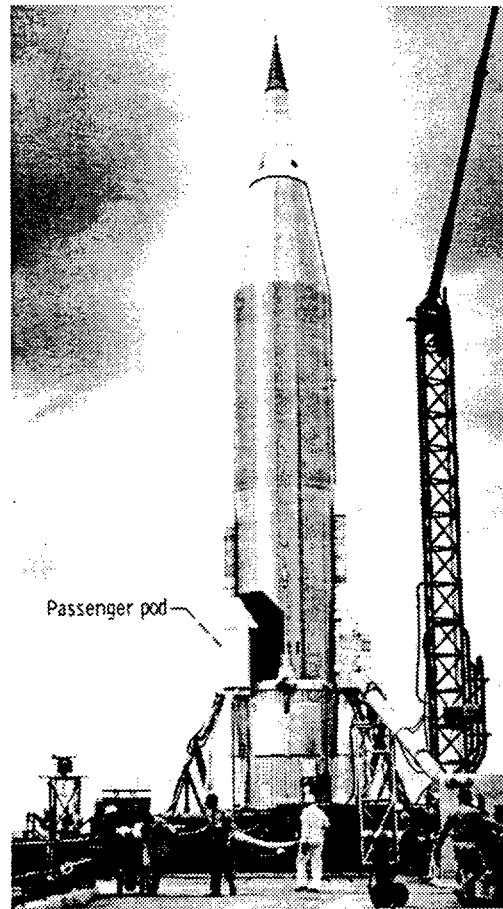


Figure 7. The experiment pod mounted on the Atlas missile.³⁷

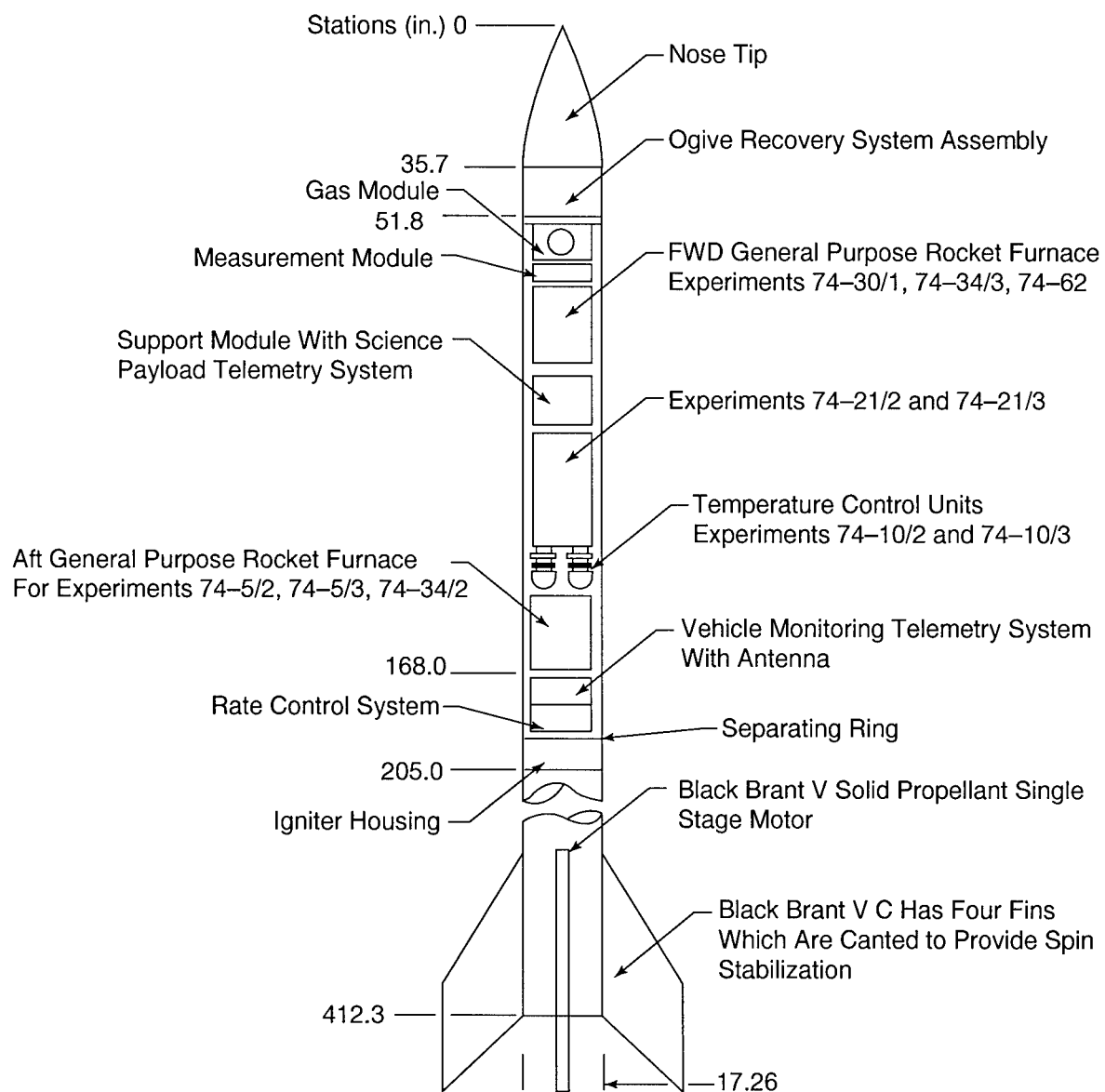


Figure 8. The SPAR 2 rocket configuration.⁴¹

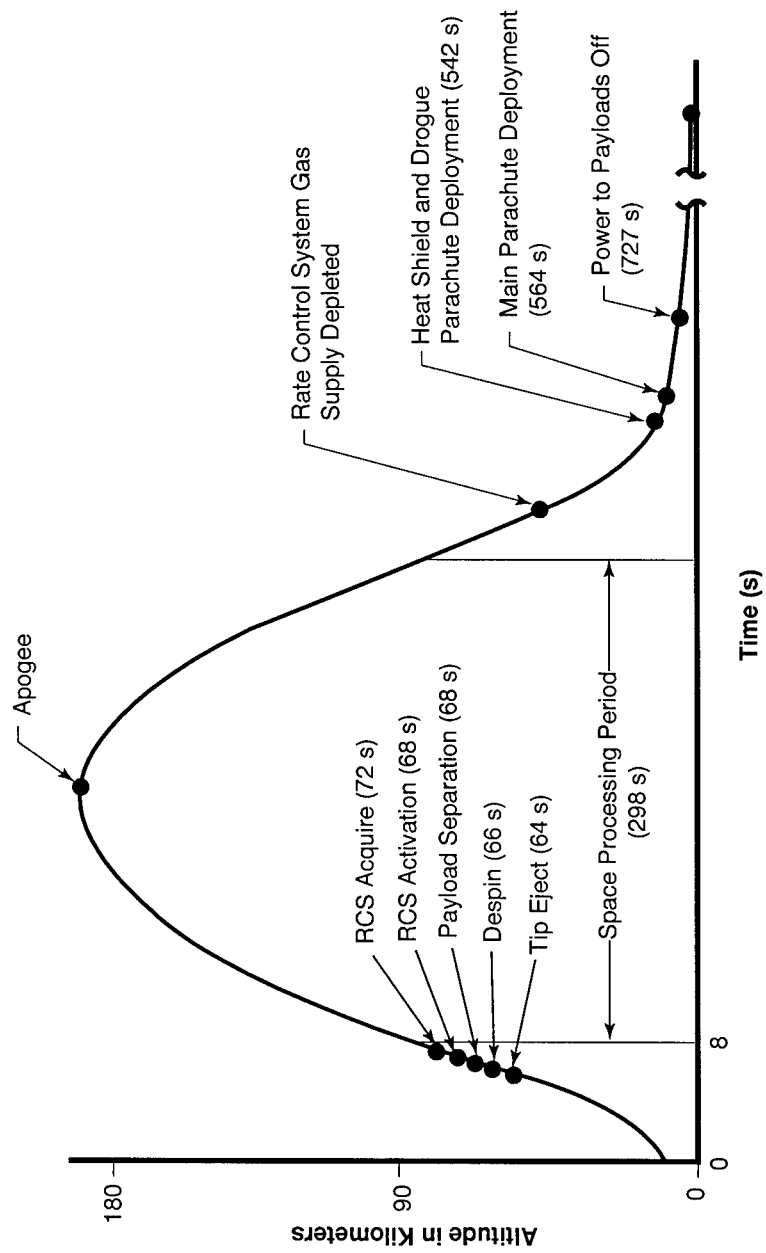


Figure 9. Flight profile of the SPAR 10.39

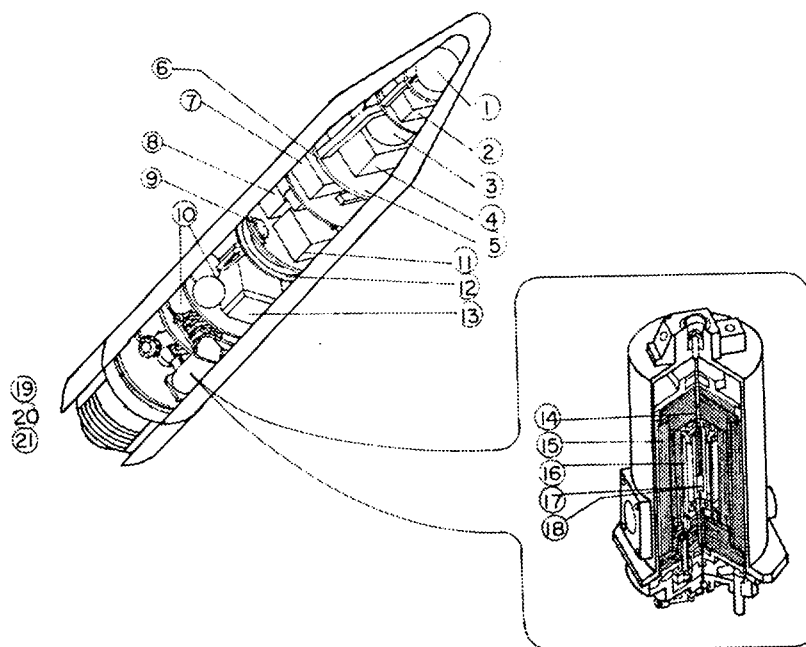


Figure 10.* Major components of the TT-500A rocket.⁴⁴

- (1) H₂ tank for gas jet system, (2) Power/sequence distribution box, (3) Control battery, (4) Control electronics, (5) Gas jet thruster, (6) Guidance transponder, (7) Inertial sensor package, (8) Tracking transponder, (9) Yo-yo despinner, (10) Cooling manipulation system, (11) Telemetry system, (12) Furnace battery, (13) Heater control device, (14) Pushing piston for test piece, (15) Bobbin type heater, (16) Melting pot, (17) Test piece, (18) Multi-layer reflector, (19) Location aid, (20) Main parachute, and (21) Drogue parachute.

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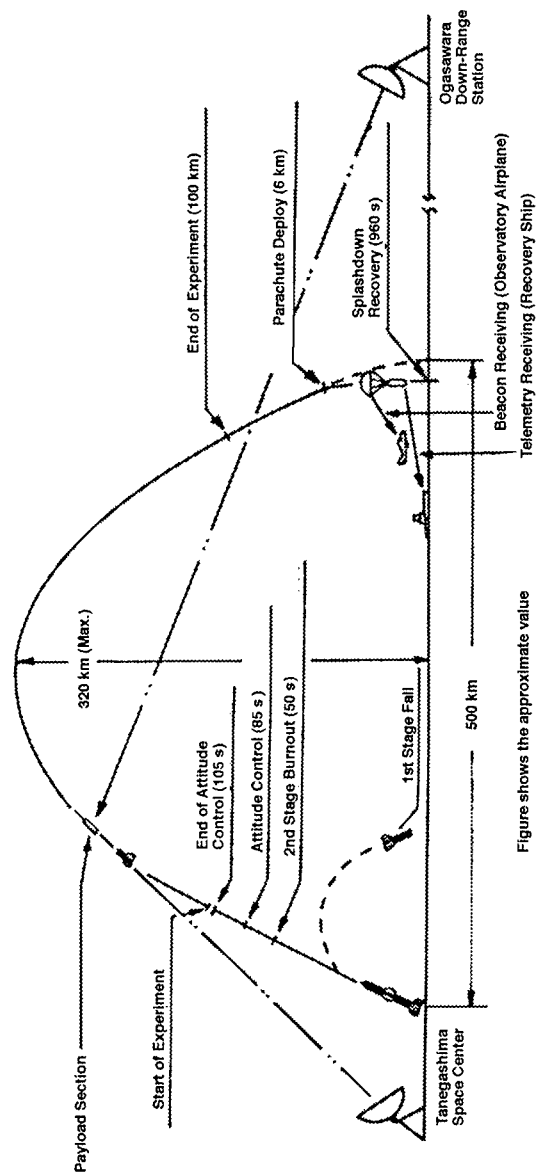


Figure shows the approximate value

Figure 11.* Typical TT-500A rocket trajectory. 44

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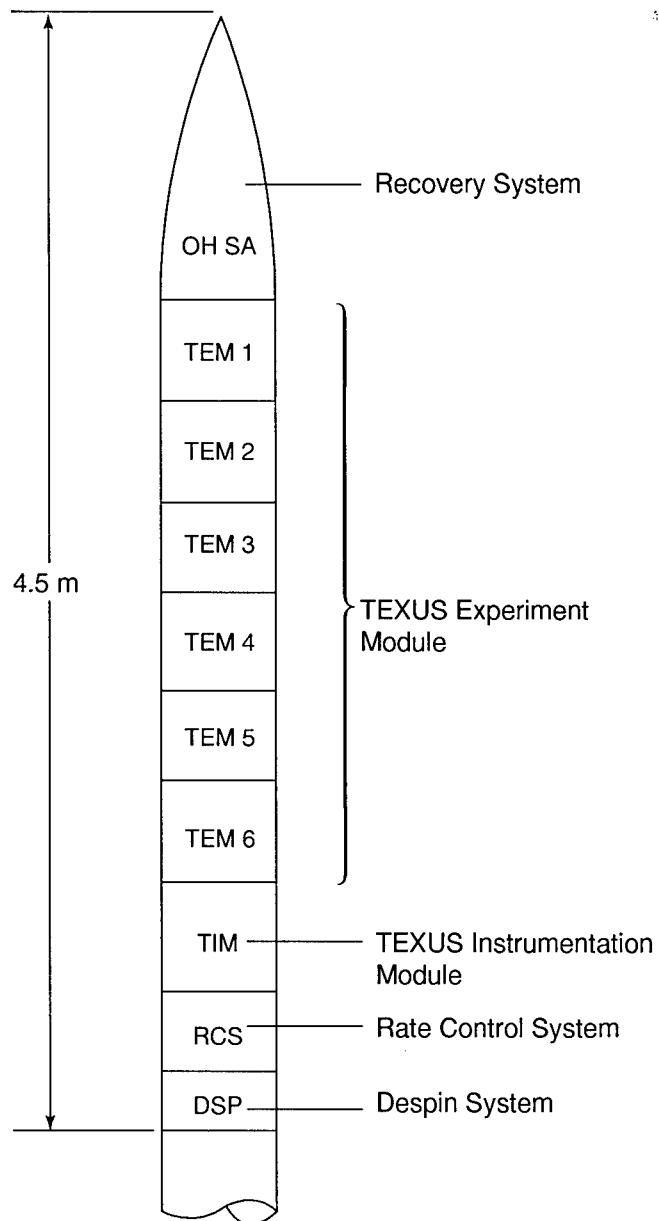
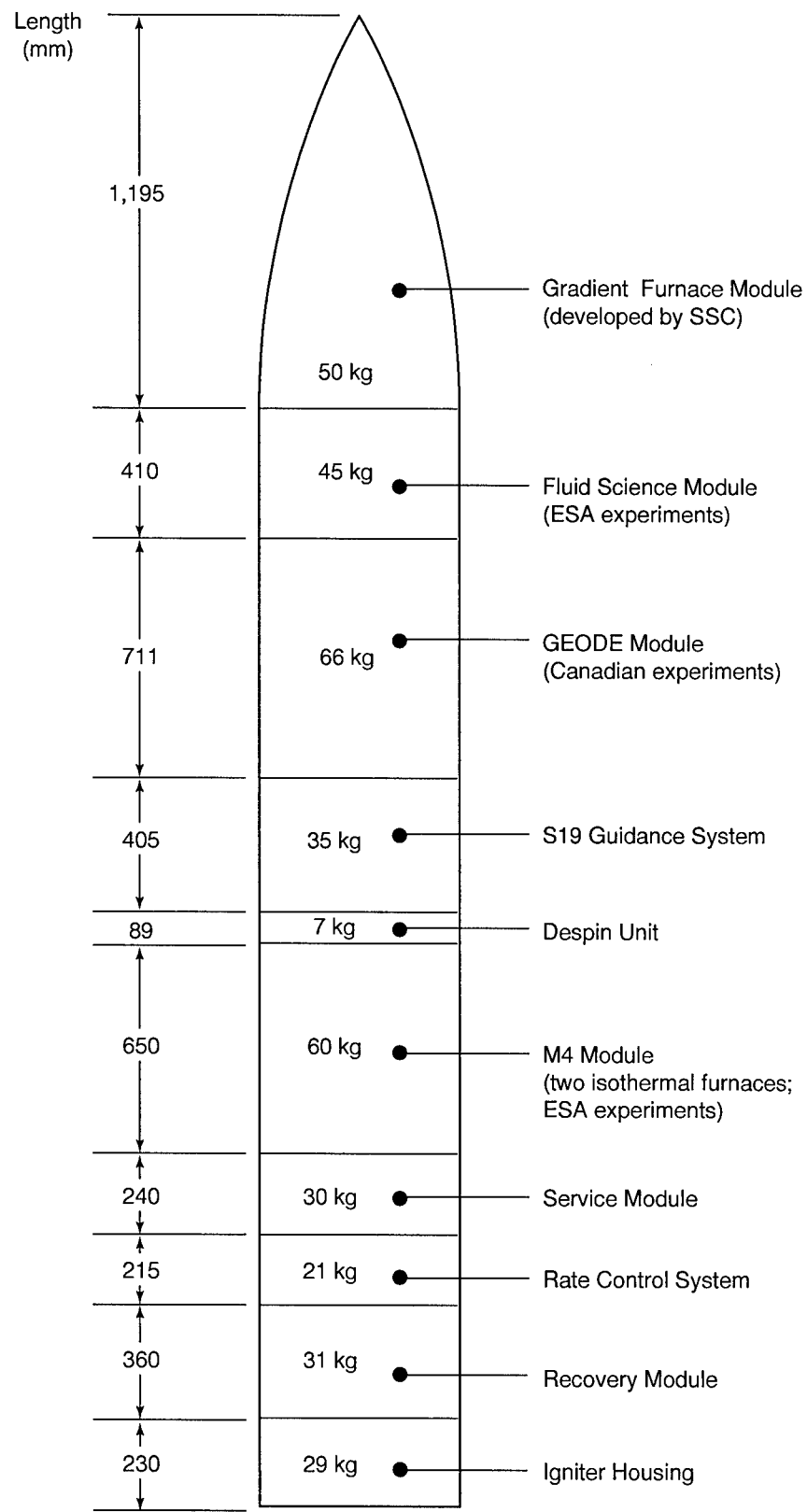


Figure 12. The payload section of the TEXUS vehicle.⁵²



Total payload weight: 374 kg Total payload length: 4,505 mm

Figure 13. The MASER 1 payload configuration.⁵⁵

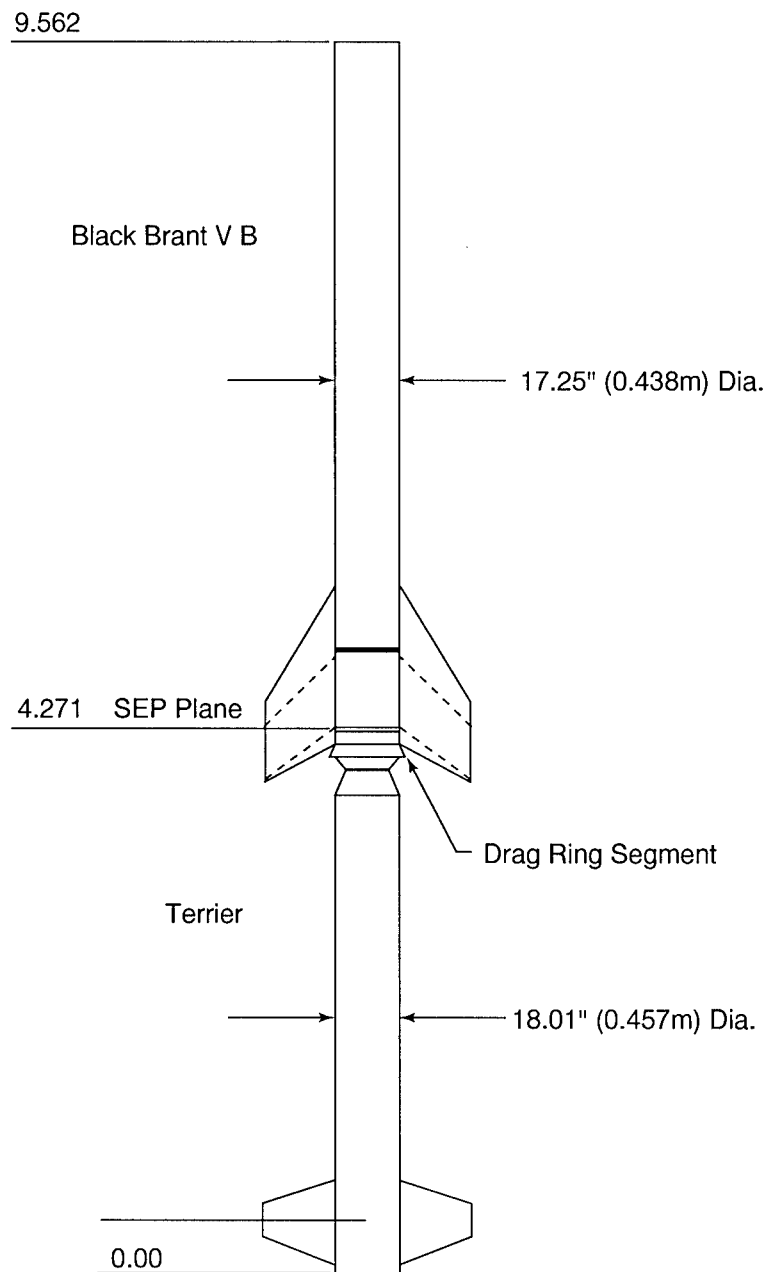


Figure 14. The MASER 1 rocket configuration.⁵⁴

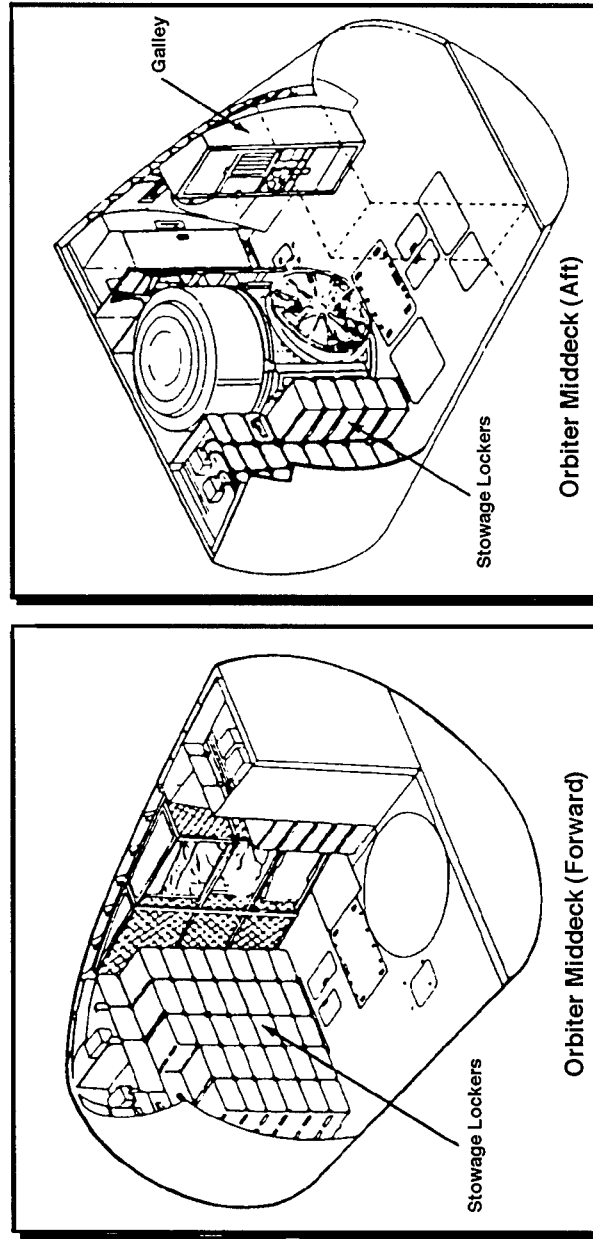


Figure 15. The forward and aft sections of the shuttle middeck.²⁰

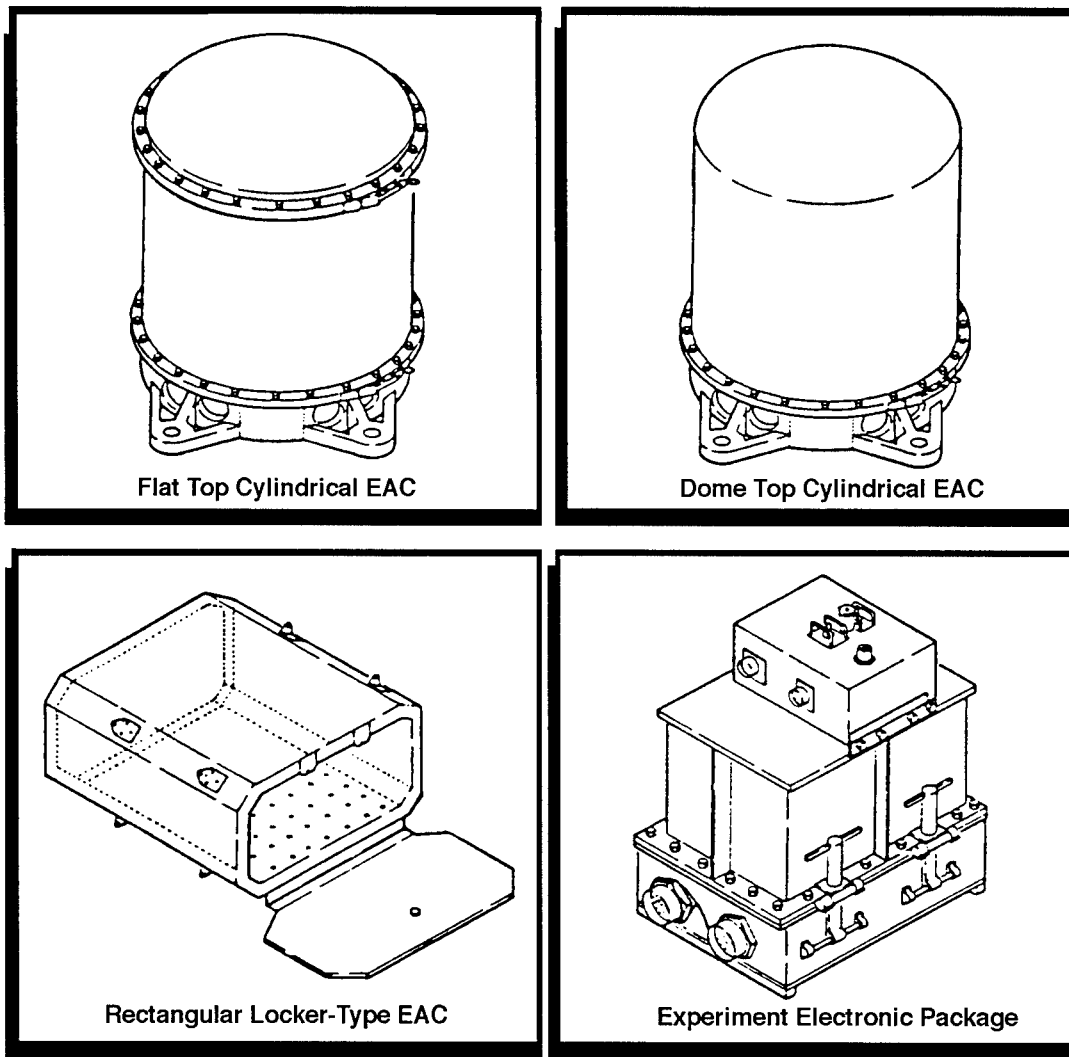


Figure 16. Experiment apparatus containers.²⁰

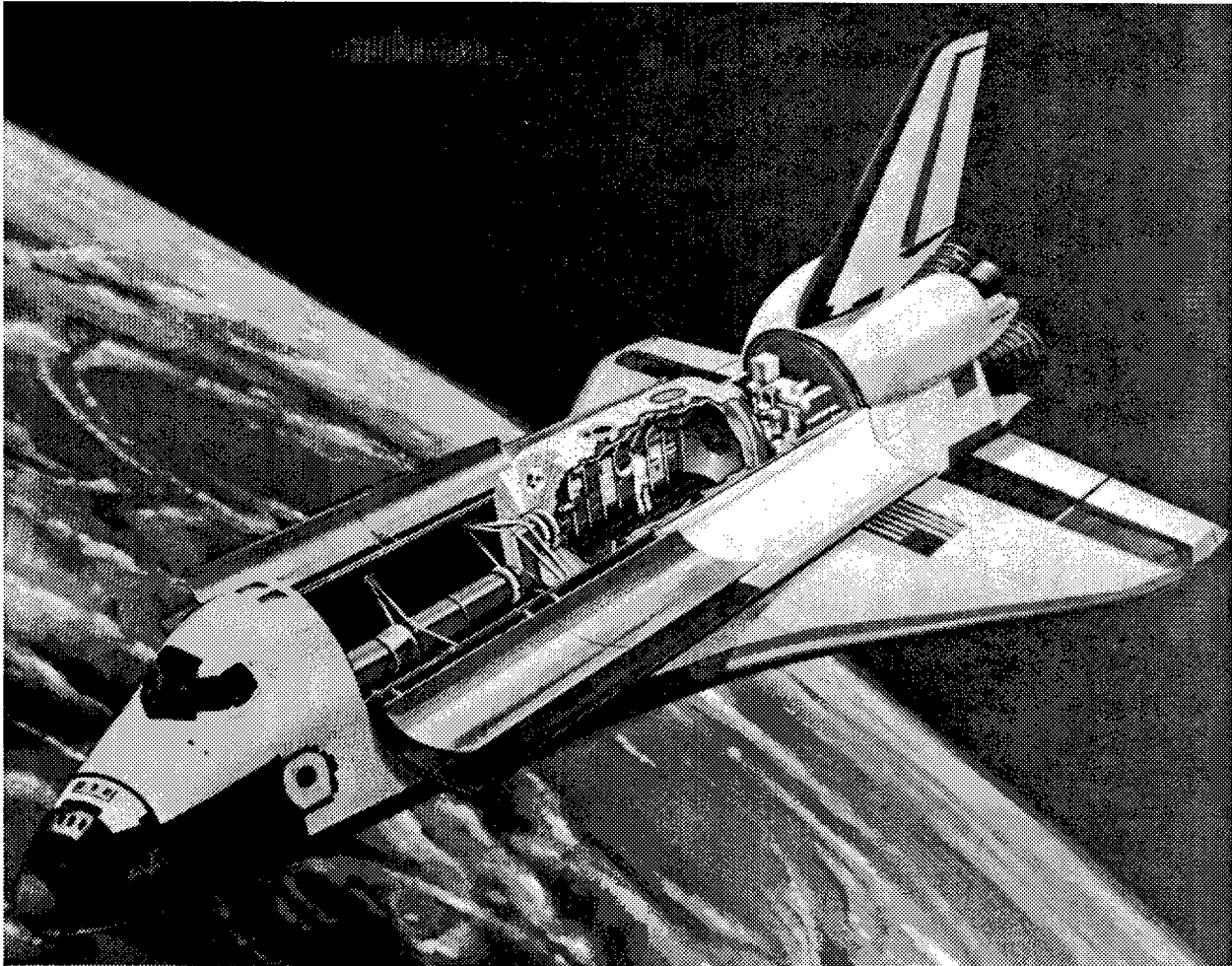


Figure 17. Spacelab module with access tunnel.⁷¹

Long Module Configuration

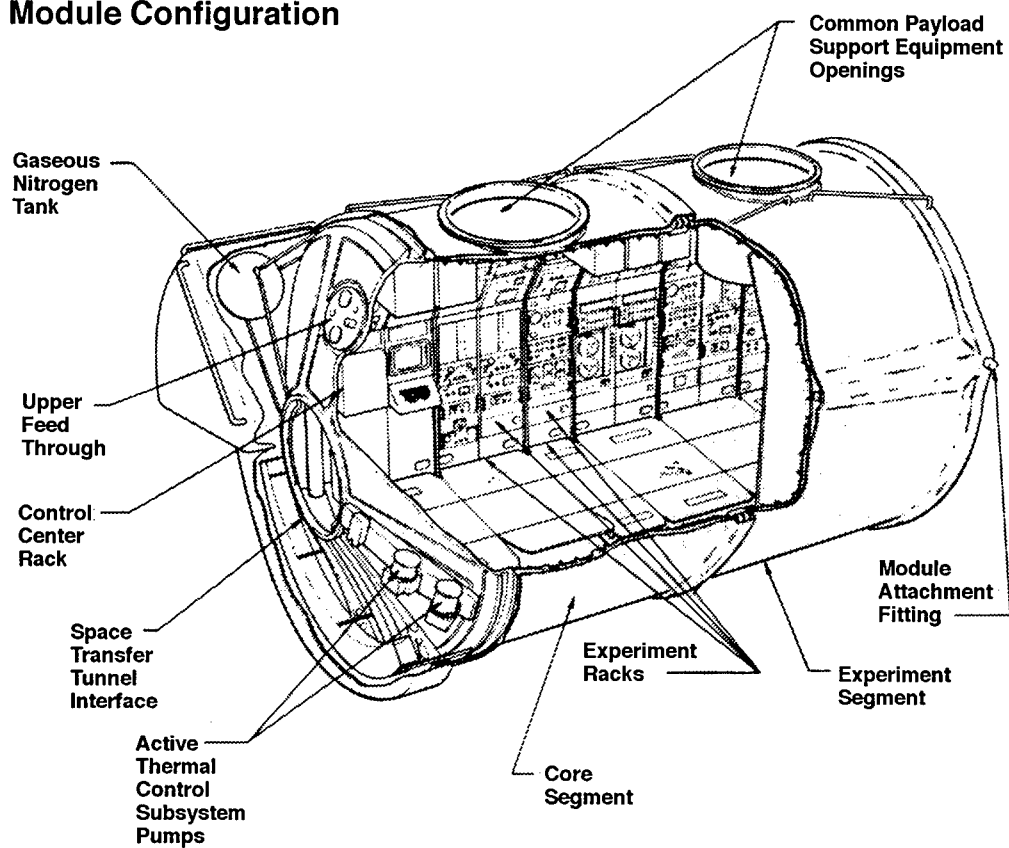


Figure 18. Spacelab long module.⁷¹

**Get Away Special
Small Self-Contained Payloads
Container Concept**

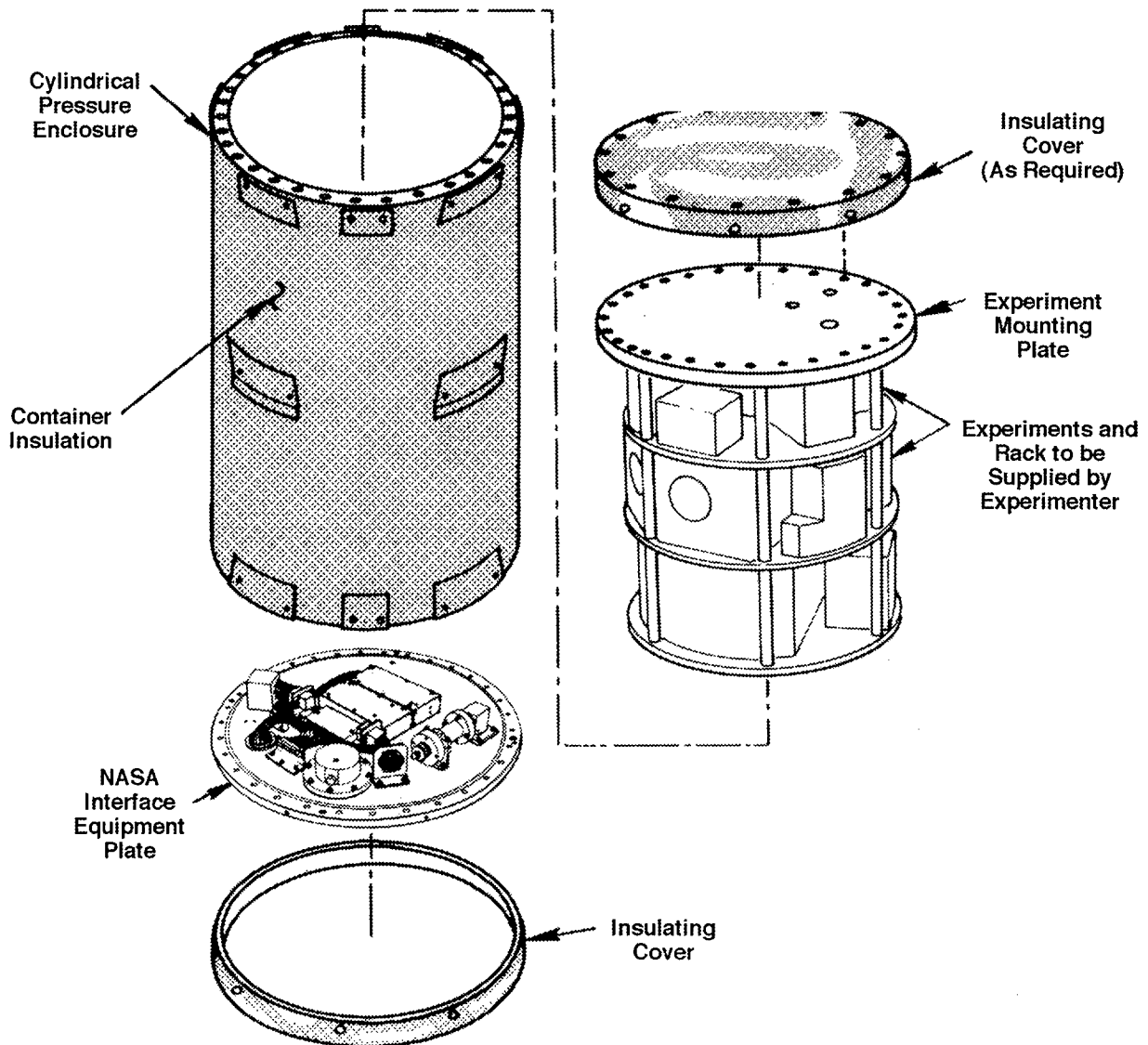


Figure 19. GAS Canister.⁸¹

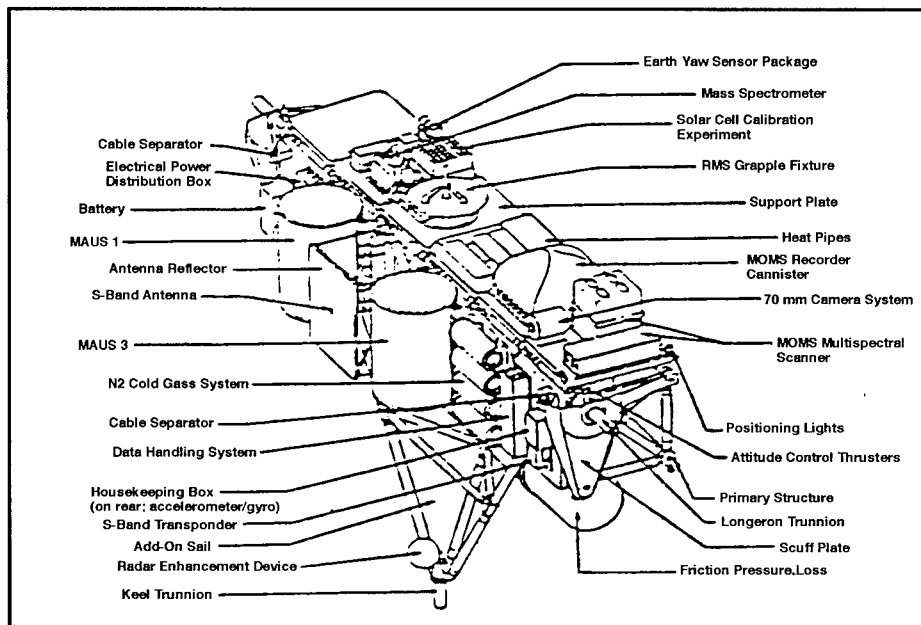


Figure 20.* The shuttle pallet satellite (SPAS).⁸⁴

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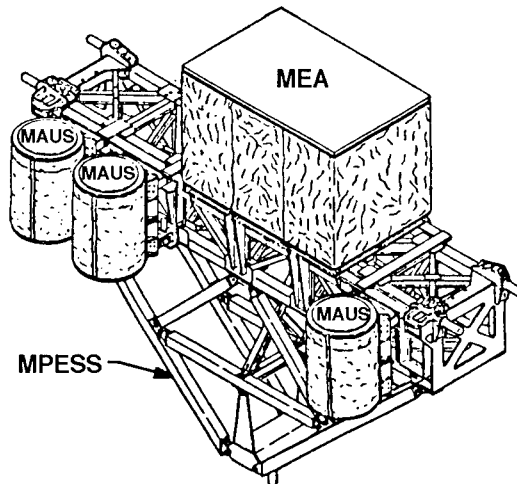


Figure 21. Elements of the OSTA-2 payload.⁹¹

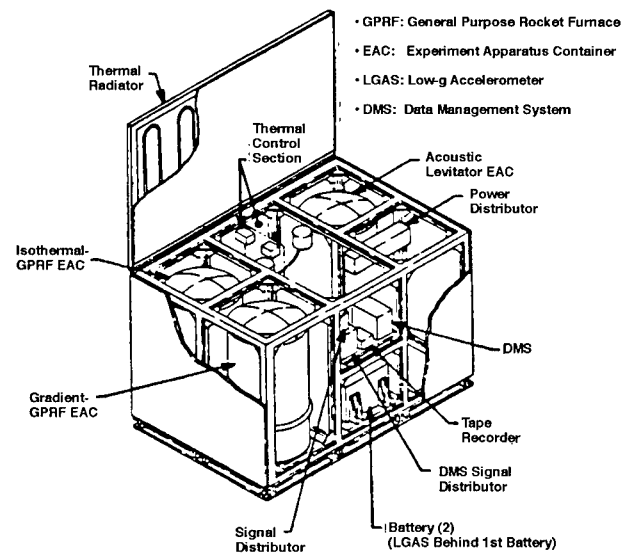


Figure 22. The materials experiment assembly (MEA).⁹¹

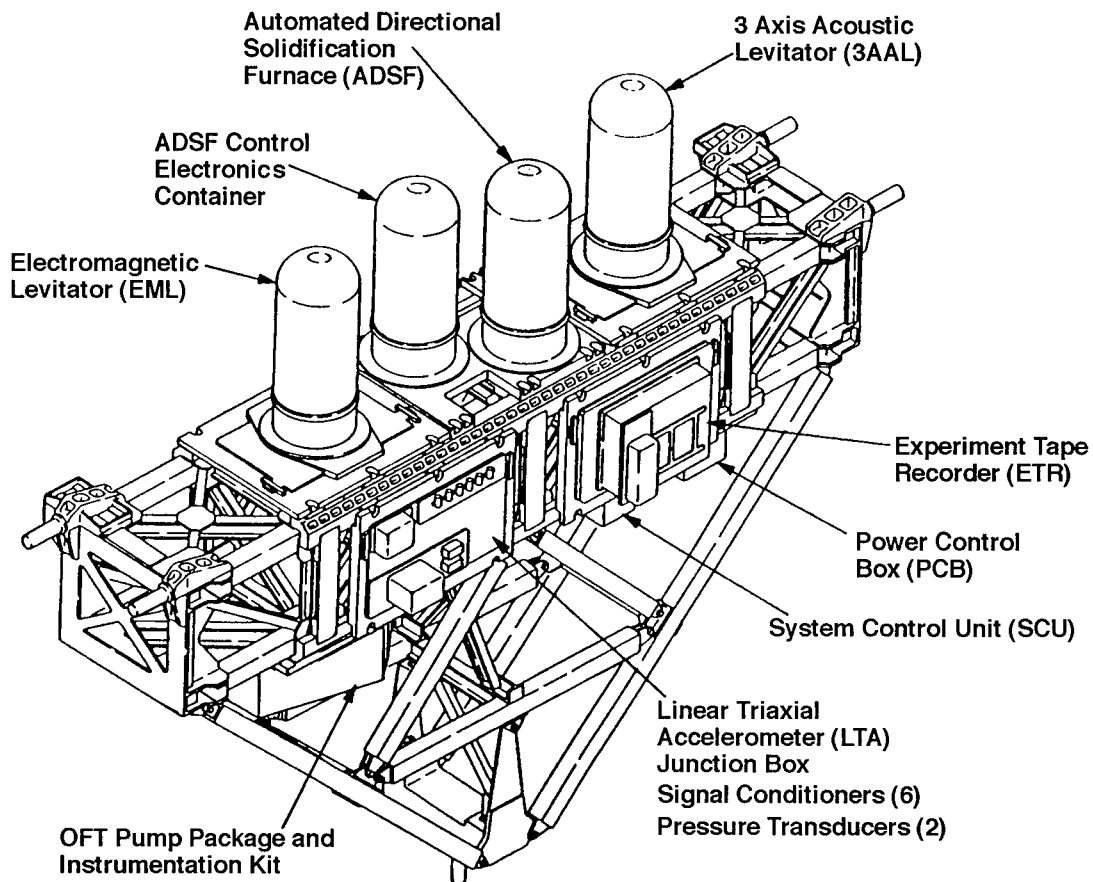


Figure 23. The materials science laboratory (MSL).⁹⁵

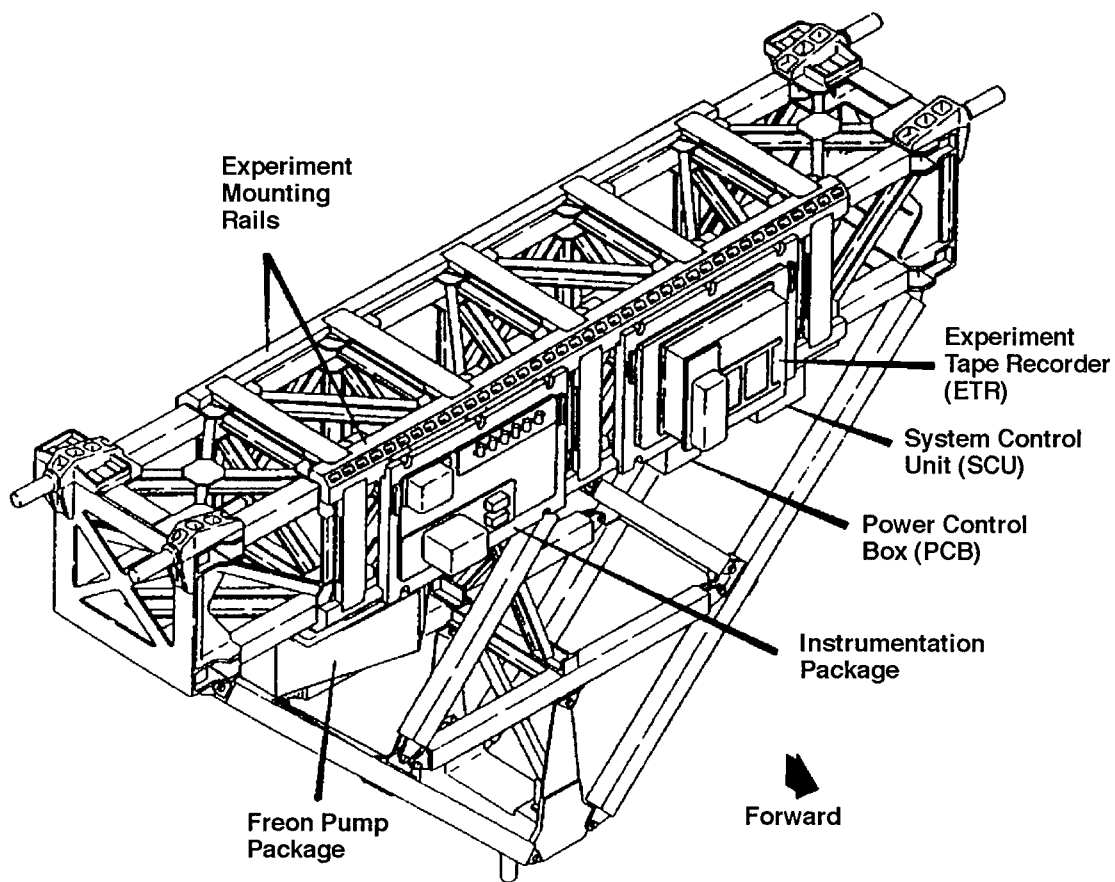


Figure 24. The U.S. microgravity payload (USMP) subsystems.⁹⁶

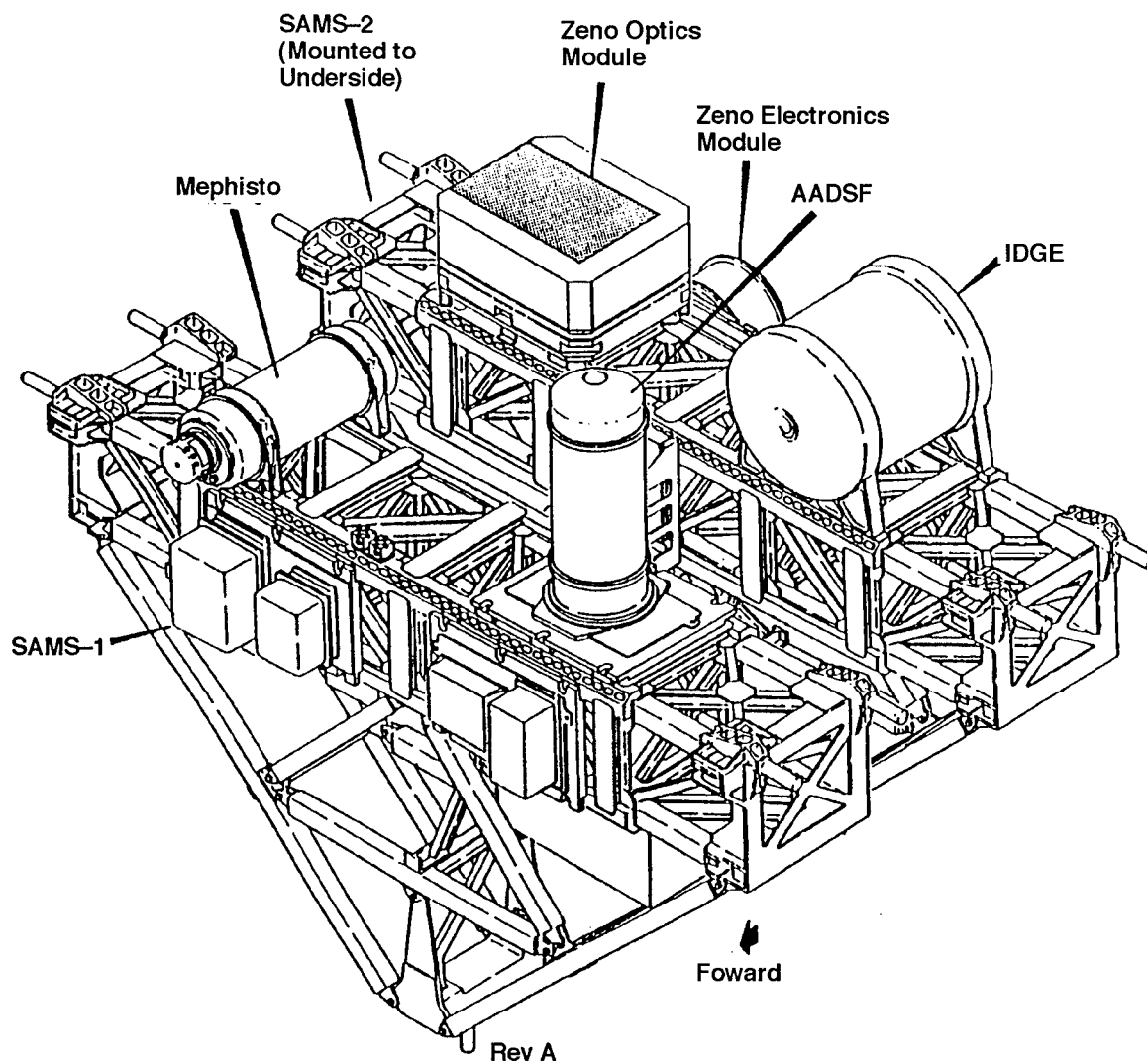


Figure 25. The USMP-2 experiments mounted on two MPES's.¹⁰²

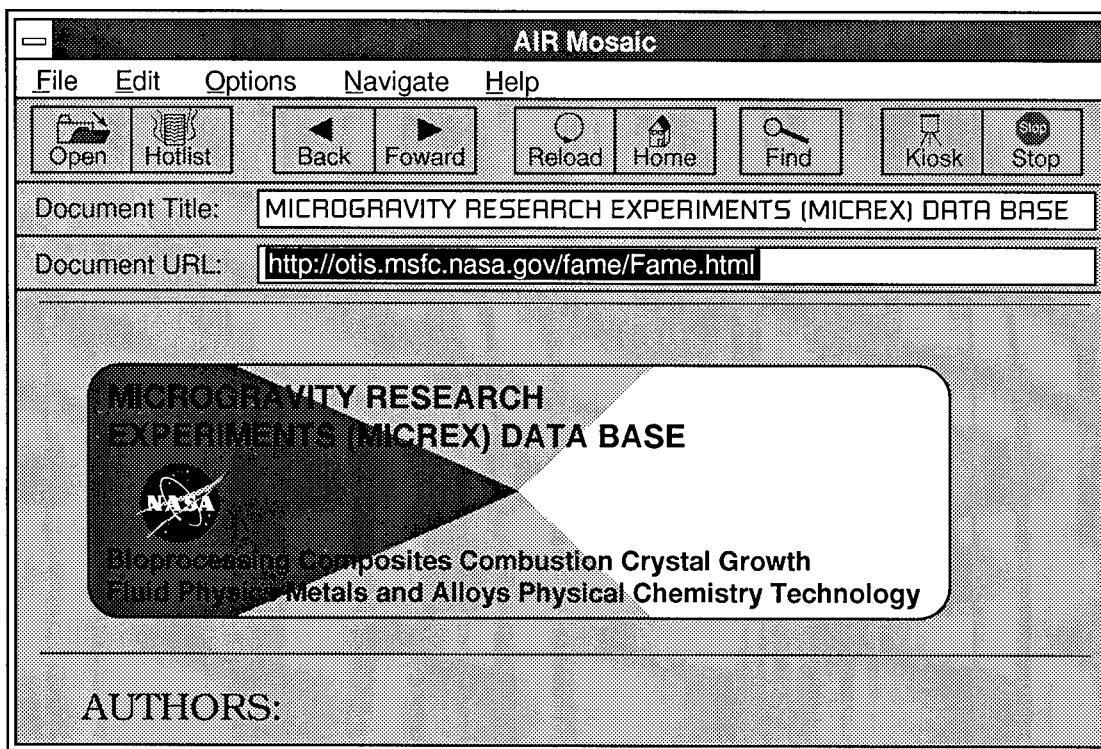


Figure 26. MICREX WWW access via Air Mosaic.

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This Key Word was generally
used to identify difficulties
in fluids and materials
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**Nb* (niobium) listed as a
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